Forest Fuel Treatments
for the
Southern West Kootenays:
A Summary of Experiences in Other Places

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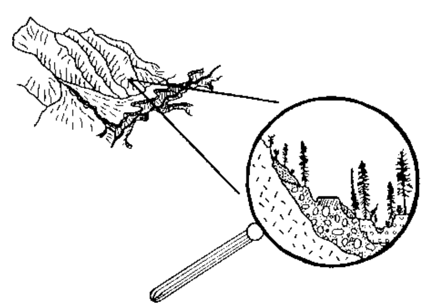

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1. Introduction

This project was initiated to explore what types of fuel treatments would likely be most effective for application in forests in the Southern West Kootenays (S WK). The project has primarily involved a focused literature review of studies that assessed the efficacy of fuel treatments where those treatments have been tested under active wildfire conditions.

There is a growing body of literature addressing this issue; however, it is mainly limited to areas of drier forest types in the Western US dominated by Ponderosa pine (Py) and mixed stands of Douglas fir (Fd), Ponderosa pine (Py), western larch (Lw), lodgepole pine (Pl), and grand fir (Bg) and dryland forest species that do not occur in BC. Although these drier forests and similar ones occur in some parts of the S WK, much of the Kootenays are presently occupied by wetter forests with significant occurrences of western redcedar (Cw) and western hemlock (Hw). However, due to climate change, all the lower elevations of the S WK are projected to have similar environments to those covered by the drier forest studies within the next 5 to 6 decades (Utzig 2012). Therefore, the studies referenced in the review are likely applicable for most areas considered for fuel treatments today, even if those environments are not present there today. There is some additional information for drier high elevation stands with Englemann spruce (Se), subalpine fir (Bl) and lodgepole pine (Pl), with mixed fire regimes similar to what occur in mid elevations of the S WK (e.g., Hessburg et al. 2016). There was very limited information found on potential treatments in wetter high elevation forests, and information that is available generally indicated that fuel treatments may not be appropriate or effective in those environments (Halofsky et al. 2018).

2. What are fuel treatments?

There are three main elements that affect the intensity and spread of wildfires: weather, topography and fuel (Graham et al. 2004). The first two are beyond our control, while there are opportunities to change the third. Fuel treatments are activities carried out to change the amount and distribution of forest fuels with the intent of changing fire behaviour (Martinson et al. 2003). The intent is to reduce the intensity and/or rate of spread of a wildfire, to reduce the risk of initiation and/or propagation of a crown fire, and reduce the likelihood of ember generation. Fuel treatments are not intended to, nor will they, decrease the occurrence of wildfire ï only change its behaviour. Fuel treatments can be completed by various techniques, including hand tools, machinery, prescribed fire or combinations of these.

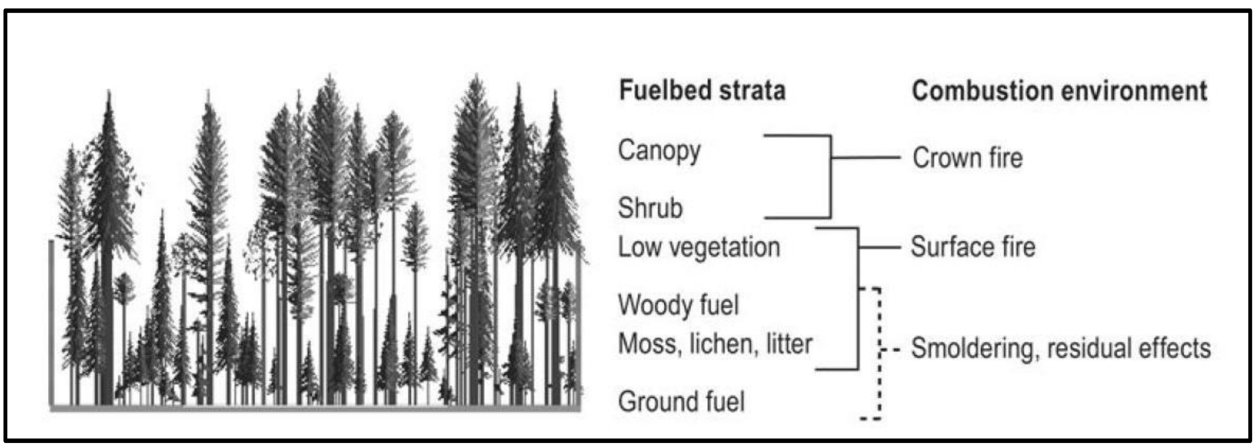

Figure 1. Fuel strata within a forest and how they contribute to different types of wildfires (from Peterson et al. 2005).

Fuel treatments can be applied to meet various objectives:

- ecosystem restoration on sites where fire exclusion has allowed forest infill to reduce ecosystem resilience, allowing the re-introduction of natural fire regimes;
- to increase the likelihood of trees/ forest ecosystems being able to survive a wildfire;
- to create defensible space to allow fire fighters to be able to initiate backburns in efforts to control wildfires; and/or
- to provide protective fuel breaks around structures or communities, thereby reducing fire intensity, and allowing fire fighters the ability to defend those areas against a wildfire.

Forest ecosystems are dynamic and continually changing in relation to evolving conditions. Without maintenance treatments, young trees, shrubs and grasses will eventually re-establish fuel loadings over time. Therefore fuel treatments are not a single event, but rather an ongoing activity required to maintain their effectiveness (Reinhardt et al. 2008).

The highest priority for administering treatments is often assigned to the Wildland Urban Interface (WUI), the area immediately surrounding communities. Due to the possibility of fires spreading through ember showers, the WUI is often designated as a 2 km buffer around major clusters of structures, or important infrastructure.

Fuel treatments as defined here should be distinguished from FireSmart programs. FireSmart treatments are centered on an individual structure or site, and radiate out with the intent to minimize the likelihood of ignition of that structure or the vegetation on that site (https://www.firesmartcanada.ca/what-is-firesmart/). The treatments described here would generally apply to the outer FireSmart zone and beyond.

3. Fuel Treatments in BC and Elsewhere

In 2004, former Manitoba premier Gary Filmon released his report on the 2003 Kelowna fire that destroyed hundreds of homes and businesses, and resulted in three deaths (Filmon 2004). Up to that time, 2003 was the worst fire year on record for the province of BC. The Filmon report estimated that there was roughly 400,000 hectares of interface forest that should be treated to reduce risks to communities throughout the province. A subsequent Provincial Strategic Threat Analysis put the total high risk area at about 685,000 ha. (FPB 2015).

In 2015 the Forest Practices Board completed a Special Investigation of Fuel Management in the Wildland Urban Interfaces of BC (FPB 2015). The FPB indicate that is was difficult to determine how much interface area had been treated since the Filmon report, as the province did not separate traditional harvesting from actual interface fire treatments within the WUI. The FPB report indicated that likely only about 45,540 ha had been treated by March of 2015, or just over 10% of what was needed.

The 2017 BC Provincial Strategic Threat Analysis Update estimated that within the 2 km WUI area there was approximately 1 million hectares of high risk Crown Land (not including high risk private lands in the WUI; BC Wildfire Service 2018). The number has increased for a number of reasons: increased data on rural structures, increased development in rural areas, better data on fuel types, etc. The Regional District of Central Kootenay (RDCK) has been preparing Community Wildfire Protection Plans over the past few years to identify priority treatment areas within the RDCK (https://rdck.ca/EN/main/services/emergency-management/community-wildfire-protection-plans.html). Since 2015, significant funding has been made available for preparing and implementing treatment plans; however, the area treated to date is still a small fraction of that requiring treatment.

In the US there are extensive programs to treat fuels, and significant ongoing research to better understand the benefits and costs of those treatments. The following sections summarize some of that research and experiences with those treatments. However, a recent review of fuel treatments in the US also indicates that the current rate of treatments is insufficient (Vaillant and Reinhardt 2017).

4. Climate Change

In the Filmon report following the Kelowna fire in 2003, climate change was only mentioned once, and then only as something that may or may not have been a contributing factor (Filmon 2004). Awareness around the impact of climate change on wildfire frequency, intensity and extent has changed dramatically since 2003. The extensive wildfires of 2017 and 2018 in BC, along with recent major fire seasons in nearby Alberta and Washington state have shown that the effects of climate change on wildfire are no longer just a theory.

A scientific article published in January of 2019 regarding the BC wildfire season of 2017 has shown that due to climate change-induced maximum temperatures and dry conditions, ñthe eventôs high fire weather/behavior metrics were made 2ï 4 times more likely, and that anthropogenic climate change increased the area burned by a factor of 7ï 11ò (Kirchmeier-Young et al. 2019). A recent West Kootenay climate change study completed for the BC Future Forest Ecosystem Council, based on modeling of future climates for the region, projected increases in average annual area burned of at least 4 times, and likely 15 times, for the S WK by the 2050s (Utzig et al. 2011).

Given these changes, there is a clear need to adapt to increased wildfire frequency and intensity (Schoennagel 2017, Keysera and Westerling. 2019, Jandl et al. 2019). Fuel treatments will not change the increased occurrence of wildfire, and they may not change the extent of area burned. However, treatments may protect specific targets, alter the impact of fires, and provide suppression opportunities (Jain et al. 2012, Moghaddas and Craggs 2007). Depending on the type of treatment, they may have positive or negative impacts on fire behaviour in the short or long-term, and may have mixed impacts on wildlife habitat and forest health (e.g., Jain et al. 2012, Prichard and Kennedy 2012).

Carbon sequestration by forests with fuel treatments is another factor to be considered. The literature on this topic is highly variable, with most of the conclusions based on a range of assumptions and various models. All studies recognize that there will be a loss of stored carbon immediately following a fuel treatment, and some conclude that this deficit will continue with a re-introduction of periodic burning, even in comparison to increased frequency and intensity of wildfires (e.g., Spies et al. 2017, Campbell et al. 2012, Campbell and Ager 2013). Alternatively, other studies indicate that some treated landscapes will maintain present carbon levels or even store more carbon over the long-term in an environment with a moderate to extreme fire regime, when compared to untreated landscapes (e.g., Carlson et al. 2012, Krofcheck et al. 2017, Hurteau et al. 2016 and 2019). Forest type and assumptions about future projections of fire frequency, extent and intensity, and regrowth following fire and/or treatment, likely lead to some of the differences in outcomes; however, there still remains significant uncertainty regarding the long-term impacts of fuel treatments on forest carbon sequestration (Meigs et al. 2009). Moghaddas et al. (2018) sum it up as follows:

> Whether or not fuel treatments safeguard enough carbon to offset their carbon cost depends on many factors including forest structure, existing fuel loads, expected wildfire frequency and severity, regeneration rates, fuel treatment type and intensity, and the fate of merchantable forest products. A key issue is the probability of fire occurring after treatment implementation; treatments that are not impacted by wildfire will not result in reduced potential wildfire emissions.

5. Ecosystem Restoration/ Ecosystem Resilience

In addition to using fuel treatments as a strategy to protect human infrastructure, they are also used as a tool in ecosystem restoration, and more recently as a component in building ecosystem resilience to climate change.

Various studies in the Western US and BC have indicated that fire exclusion and subsequent forest infill has led to increased fuel loads and increased fire intensity (e.g., Keysera and Westerling. 2019, Daniels et al. 2007). In the East Kootenay, since 1988 there has been an active program to restore open Douglas fir and Ponderosa pine forests and grasslands using a combination of fuel treatments and prescribed fire (https://www.trench-er.com/about). In the Western US there has also been extensive research on ecosystem restoration in dryland forests and grasslands (e.g., Omi and Joyce 2003, Hessburg et al. 2015, Haugo et al. 2015), and to a lesser extent on areas of mixed fire regimes more similar to the lower and mid elevations of the S WK (e.g., Hessburg et al. 2016). Recently there has been some discussion regarding management for areas with stand-replacing fire regimes (Halofsky et al. 2018).

Previously the emphasis has been on restoration to the past “Range of Natural Variation” (RoNV or NRV); however, as climate change advances, the emphasis is beginning to shift to building resilience to future conditions, or adapting to the “Future Range of Variation” (FRV; Haugo et al. 2015, Keane et al. 2009, Holt et al. 2012, Hessburg et al. 2016). With climate change advancing, management interventions are becoming more imperative if we want to avoid catastrophic ecosystem shifts (see Fig. 2). Fuel treatments are one example of many potential interventions (Jandl et al. 2019). Assisting with a transition to vegetation types and landscape patch configurations more suited to future climate regimes may also reduce fire severity in the future (Parks et al. 2016, Churchill et al. 2013). Some recent studies have found that fuel treatments have also increased resilience to increasing drought (e.g., Restaino et al. 2019). North et al. (2018) describe various reforestation strategies for building more resilient forests following stand-replacing disturbances, be they severe fire, insect attacks or clearcutting.

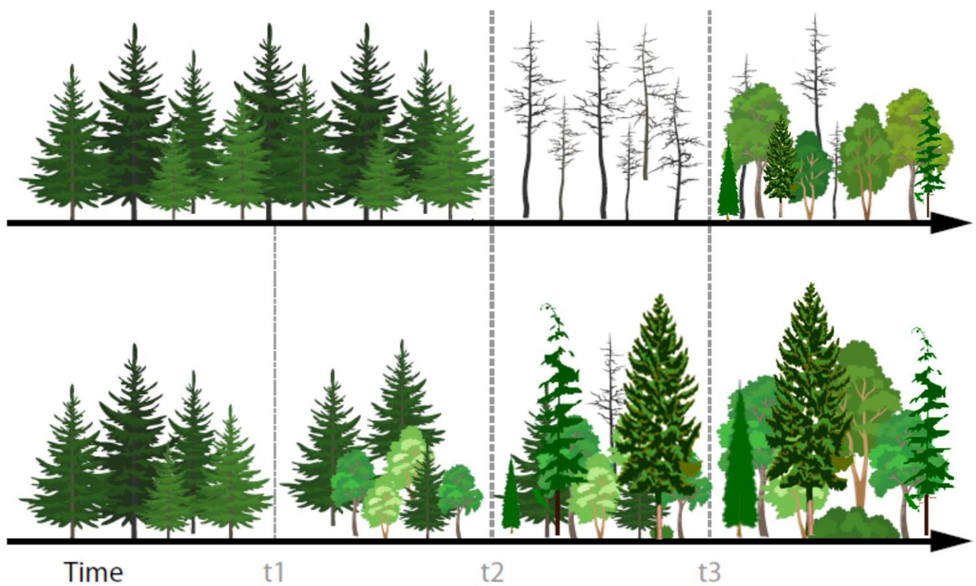

Figure 2. Possible pathways of forest development under climate change. The upper panel represents a scenario where the present stand continues until a threshold is crossed or a stand-replacing disturbance triggers its collapse (t2). On the deteriorated site, succession sets in and a new tree species composition develops (t3). Alternatively, through stand treatments the existing stand is modified to make it more resilient (t2), and the future forest transitions gradually to a future state (adapted from Jandl et al. 2019).

Under past natural conditions in the lower elevations of the S WK (mainly BEC units of ICHxw, ICHdw, ~~ICHwk~~ ICHmk and parts of the ICHmw and ICHdm), ecosystems generally experienced mixed fire regimes. On southern aspects, especially in the ICHxw, forests had adapted to frequent low intensity fires over time; with <50 year return intervals in some cases (Nebitt 2010, Greene 2011). Natural forests in those situations were generally open and dominated by large fire resistant trees (Douglas fir, Ponderosa pine and western larch - Fd, Py, Lw). Over the last century, wetter summers and fire control have eliminated most of those low intensity fires, allowing infill with dense stands of trees, including western hemlock and western redcedar. With climate change projections indicating hotter and drier conditions in the coming decades, fuel treatments in the lower elevations of the West Kootenays could be considered both ecosystem restoration and building resilience for the FRV.

6. What is an effective fuel treatment for mature stands? Based on empirical evidence – treatments actually tested by wildfire.

There is a sufficiently long history of fuel treatments in the Western US that a number of treatment areas have actually been encountered by wildfires over the last couple decades (see Figure 3). This section is primarily based on retrospective studies that have examined treatment areas following wildfires to investigate how the treatments modified fire behaviour. A sample of those studies is summarized in Appendix 1.

The studies generally fall into three types: 1) retrospective field studies where subsequent to a wildfire encountering a treatment unit, transects are placed perpendicular to the edge of the treatment area, and indicators of fire intensity are measured along the transect going from untreated into the treatment area; indicators include factors such as the percentage of the tree crowns burned, percentage of tree morality, height of charring up the tree boles and amount of fuels consumed; 2) retrospective studies where fire severity of treated and untreated areas is determined from comparing satellite imagery before and after the wildfire; fire severities within and outside the treatment areas are then compared to determine whether the treatment areas were effective in reducing wildfire severity; 3) statistical assessments of a number of retrospective studies from various fires and treatments to determine if there are trends in the effectiveness of various treatments across a variety of wildfires (i.e., ñmeta-analysesò).

Figure 3. The lower portion of the photo shows where the 2011 Wallow Fire moved downslope toward rural residences on the edge of the community of Alpine (the green tree area) as it entered the WUI treatment unit. In the treatment, the fire transitioned from a crown fire to a surface fire—with reduced burning intensity. Notice how the blackened tree crowns (totally consumed by the fire) diminish and turn to brown (fire singed) and then to green (unburned) where the homes are located (adapted from Keller 2011; photo USFS Tim Sexton; see also Kennedy and Johnson 2014 and Waltz et al. 2014).

In addition to these studies, the scientific basis and rationale for fuel treatments for drier forests are well summarized two publications by the USDA Forest Service (Graham et al. 2004, Peterson et al. 2005).

Hessburg et al. (2016) provide an extensive summary of stand and landscape treatment approaches and trade-offs for forests~~.~~ with mixed-severity fire regimes. Jain et al. (2012) describe how to effectively plan treatments, including considerations for other values such as wildlife habitat. Effective fuel treatments generally have been found to include four key elements that are described in Table 1 below.

Table 1. Basic principles of fuel treatments for increasing fire resistance for dry forests (adapted from Agee and Skinner 2005).

Principle	Effect	Advantage	Concerns
1. Reduce surface fuels (remove material on or near the ground)	Reduces fire intensity and potential flame length	Control easier; less torching*	Surface soil disturbance less with prescribed fire than other techniques
2. Increase height to live crown (removal of ladder fuels and pruning)	Requires longer flame length to begin torching*	Reduced mortality in the overstory trees and less opportunity for initiating a crown fire	Opens understory; may allow surface wind to increase
3. Decrease crown density (thin the overstory)	Makes tree-to-tree crown fire less probable	Reduces active crown fire potential	Surface wind may increase and surface fuels may be drier
4. Retain large trees of fire resistant species (e.g., Py, Fd, Lw)	Less mortality for same fire intensity (large trees have greater height to live crown and thicker bark)	Generally restores historic structure or aids adaption to future conditions; increased shade decreases regeneration and shrubs	Less economical; may keep trees at risk of insect attack

*Torching is the initiation of crown fire where flames from the ground ignite the crowns

1) Of primary importance is the need to reduce surface fuels. The purpose is to reduce the intensity and flame length of a surface fire. This makes fire fighting easier and reduces the likelihood of torching ï fire propagating from the ground to tree crowns (i.e., igniting a passive crown fire). This may mean cutting, piling and burning, or otherwise removing small trees and dead branches on or near the ground. It can also include mastication ï using large machines to chop up this material into fine pieces and distributing it on the forest floor. Alternatively, or sometimes in combination, prescribed broadcast burning can be used to remove surface fuels.

2) Increasing the height to live crown from the ground also decreases the likelihood of fire propagating from the ground to the tree crowns (i.e., igniting a passive crown fire). This involves removing smaller and intermediate trees also known as ladder fuels, and is often referred to as thinning from below. It can also involve pruning lower branches on retained trees.

3) Where the density of trees in the main canopy creates sufficient continuous fuel in the canopy to propagate fire moving from tree crown to tree crown, thinning of the overstory may also be required to reduce the likelihood of an ñactiveò crown fire. The objective is to reduce ñcanopy bulk densityò to a level that the risk of an active crown fire is minimal, but not so much as to open the stand to increased winds, nor significantly decreased shade that leads to increased drying of surface fuels and increased regeneration. Reduced density has also been found to increase drought tolerance of retained trees, and resistance to insect attacks.

4) Retention of the largest diameter fire resistant trees is also of major importance (in the S WK, Ponderosa pine, Douglas fir and western larch). Large trees generally have the greatest height to live crown and the thickest bark, and therefore are most likely to survive a surface fire. They are also the most

likely to endure drought, and offer the best opportunity for climate change resilience. Retaining these does create economic tradeoffs in treatment costs, but is an important element to a successful treatment.

Based on the articles summarized in Appendix 1, general guidelines for shaded fuelbreak treatments should include the following as a minimum, whether applied in the wildland urban interface or other key landscape locations (see also Figure 4):

- Surface fuel treatments are essential ï prescribed broadcast burning following fuel reduction is preferred, pile and burn is second best, and mastication is least desirable ï thinning and/or cutting ladder fuels without treating slash will create worse conditions than no treatment at all (e.g., Agee and Skinner 2005, Martinson and Omi 2013, Safford et al. 2012, Raymond and Peterson 2005, McIver et al. 2013).
- Thinning from below to remove ladder fuels to increase height to live crown and decrease crown bulk density is desirable in most cases. The largest, fire resistant, and preferably windfirm trees should be retained. However there are tradeoffs; opening the stand too much can lead to loss of effectiveness due to increased wind exposure, faster forest regeneration of conifers and/or introduction or spread of flammable grasses and shrubs (e.g., juniper, snowbrush, Oregon grape). Regeneration and retention of less flammable deciduous trees and shrubs should be encouraged (e.g., aspen, cottonwood, maple, thimble berry). Rate of conifer regeneration and succession will determine the frequency and costs of maintenance for a fuel treatment (e.g., Johnson et al. 2007).

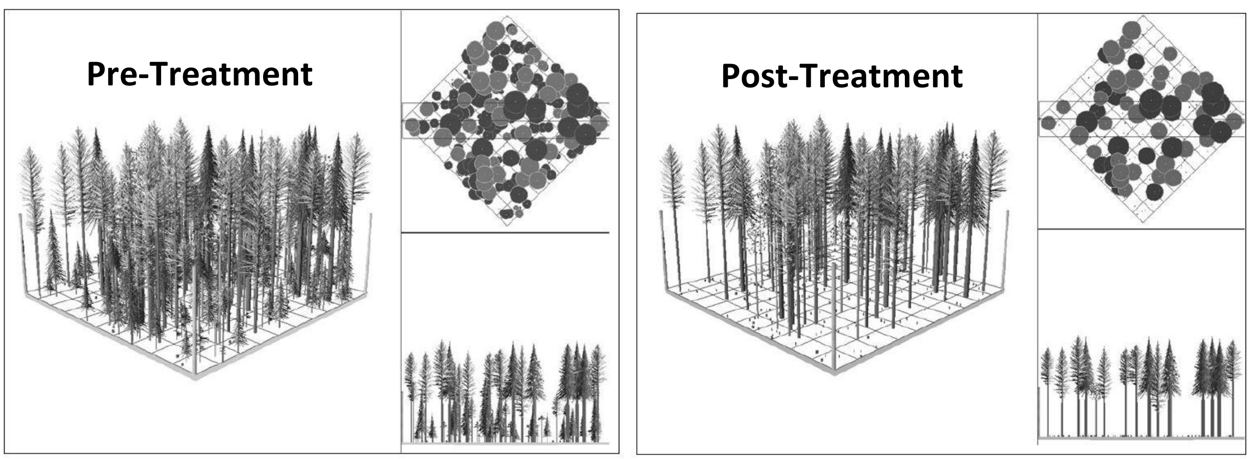

Figure 4. Visualization of a typical stand before and after fuel treatment. The treatment in this case was removal of all stems less than 23 cm. in diameter (adapted from Peterson et al. 2005).

Based on a review of the references summarized in Appendix 1, the following potential retention targets are suggested for intermediate, mature and older stands to maximize shaded fuel break benefits, minimize probability of passive or active crown fire, and minimize maintenance treatments (these will vary depending on site, species and objectives):

- Stems/ ha: target of 100 to 250 st/ha, depending on spp., stem diameter, crown size, site, etc.
- Basal Area (m2/ha): target 10 to 30, depending on spp., stem dia., crown size, site, etc. (10-20 generally has minimal extra benefit to crown fire risk reduction, and could have negative impacts on wind and shade; less than 10 has no extra benefit to crown fire risk)
- Crown Bulk Density (kg/m3): target of 0.04 average, (0.04 to 0.08 generally acceptable; less on steeper slopes; less than 0.04 has no extra benefit)
- Crown Closure: approx. 20-40% (a balance between crown bulk density, crown spacing, shade and wind exposure; lower crown closure is acceptable on southerly aspects and drier sites, more for toe slopes and north aspects)

- Inter-crown Spacing: target 3-4 m average, minimum 2 m average (isolated clumps are acceptable, and have benefits for habitat diversity and ecosystem resilience)
- Canopy Base Height: target of 9 m, minimum 4 to 6 m average
- Retained Tree Species and Diameter: largest possible, preferably fire resistant species (Py,Fd,Lw); >30 cm generally found to be advantageous; where these spp. are not present in sufficient amounts, consider leaving other spp. in lower density, and planting fire resistant spp. with heterogeneous spacing; risk of drought, windthrow, insects and disease are also important considerations

Treatments that are reported in the literature are highly variable, and often selected to suit specific ecosystems, stand conditions and socio-economic situations. The recommendations described above are the author's synthesis and interpretation of the literature applied to S WK ecosystems and stands, and therefore no single reference is applicable to the recommendations. Appendix 2 provides some further information on basal area, crown bulk density, crown closure, crown spacing and key references.

Given the above, there is still significant uncertainty about how a fuel treatment will interact with a wildfire. As stated in the first section, fire behaviour depends not only on the amount and distribution of fuels but also weather and site conditions. Temperatures, humidity and winds preceding and during the wildfire will determine the condition of the fuels, as well have a dramatic effect on rate of fire spread and the intensity of the fire as it encounters the treatment. Interaction of fire weather and local topography of the treatment site will also have significant effects. Given the projected increases in extreme weather, it is prudent to plan treatments for encountering extreme fire conditions.

Subsequent sections touch on related subjects, such as planning treatments, modeling, landscape level considerations and potential non-fire impacts and benefits of fuel treatments. The Appendices provide other potentially useful information.

7. What do modelling results say about fuel treatments?

Numerous studies have modeled the effectiveness of a range of treatments in various forest types and wildfire conditions. Many studies have shown that fuel reduction treatments are potentially effective in reducing intensity and severity of wildfire, and decreasing suppression costs (e.g., Spies et al. 2017, Thompson et al. 2017, Johnson et al. 2007). Modelling studies have also demonstrated potential benefits of fuel treatments for other values such watershed protection (e.g., Jones et al. 2017, Roche et al. 2018).

Modelling of the interaction between treatments and wildfire at the landscape scale has also increased our understanding of the longterm impacts of constraining the types and locations of management treatments (Barros et al. 2017). Because the area treated and the area affected by wildfire are only a small percentage of the landscape at any given time, the treatments may result in short-term reductions in area burned, but will likely have little effect on the overall fire regime over the long-term.

However, modeling studies have also shown that treatments often have trade-offs with other resource values such as timber supply, economic opportunities and risks to infrastructure. There are also ecosystem trade-offs, including wildlife that depend on closed forest habitats vs. species requiring open habitats (e.g., Spies et al. 2017, Tempel et al. 2015). Some modeling studies are designed specifically to aid in understanding the potential trade-offs between various values (e.g., Ohlson et al. 2006, Stevens et al. 2016).

8. Maintenance of Treatment Areas

As with any activity, good planning and prevention are always better than after-the-fact maintenance and repair. Ecosystems are dynamic and will respond to any disturbance, including fuel treatments. Most of the studies reviewed in this project indicated that any treatments will eventually require maintenance to maintain their effectiveness (e.g., Reinhardt et al. 2008). The cost and frequency of maintenance will depend on the ecosystem and environmental characteristics of the treatment unit, its disturbance history, and the type of treatment applied. Most of the studies reviewed indicated that treatments are expected to begin to loose effectiveness in 5 to 15 years, and become generally ineffective after 20 years (e.g., Collins et al. 2009, Martinson and Omi 2013, Graham et al. 2004, Fernandes and Botelho 2003, Prichard and Peterson 2011).

Treatments that maintain sufficient shade to discourage regeneration of conifers and flammable shrub communities are likely to require less frequent maintenance (e.g., Jain et al. 2012, Johnson et al. 2007). Treatments that are designed to allow for treatment with prescribed fire are also likely to be more cost effective, as prescribed fire can then be used as a maintenance treatment. Given the uncertainty of funding for future maintenance treatments, tradeoffs between primary treatment costs and maintenance costs should be carefully weighed in designing primary fuel treatments.

9. Landscape Considerations

Comprehensive discussion of the topic is beyond the scope of this project, however a few comments and references are provided. The importance of location and overall layout of treatment areas was noted in many articles, both at the scale of the treatment unit itself, but also at the landscape scale. One of the key findings from Graham et al. (2004) summarizes the concept: ñModels and observations of landscape scale fire behavior and the impacts of fuel treatments clearly suggest that a landscape approach is more likely to have significant overall impacts on fire spread, intensity, perimeters, and suppression capability than an approach that treats individual stands in isolation.ò

Past fire history and the presence of previously burned areas can play an important role in planning at the landscape and regional scales. Some authors suggest that fuel treatment areas anywhere in the vicinity of communities or other targets for protection from fire can be beneficial in reducing fire effects severity by providing ñspeed bumpsòfor advancing wildfires (Kennedy and Johnson 2014). Allowing wildfires to burn under some circumstances can also be used to create landscape patterns that may aid in reducing the extent of high intensity fires in the future.

Some relevant references regarding landscape treatment planning are noted below:

- Graham et al. 2004 ï describes the importance of strategic landscape design in treatment planning and prioritization
- Ager et al. 2017 ï modeling of allowing more area to burn under moderate fire conditions as a means of reducing the area burned under extreme conditions ï good discussion of trade-offs
- Hessburg et al. 2015 ï extensive descriptions of principles for management of fire regimes at the landscape level
- Prichard et al. 2018 ï modeling and case studies looking at the interactions between past burns and future burns with regard to severity, spread and area burned (one case study in BC)
- Stevens-Rumann et al. 2016 ï using three case studies explores the relationship between areas previously burned and fire severity when they are reburned (one case study in BC)
- Hessburg et al. 2016 ï good discussion of landscape level considerations in applying fuel treatments in mixed-severity fire regime forests
- Halofsky et al. 2018 ï a general discussion of wildfire management in landscapes dominated by high severity stand-replacing fires and long return intervals

10. Other Potential Costs and Benefits of Fuel Treatments

Planning will also require consideration of other forest values that may be impacted by fuel treatments. These will include terrestrial, riparian, wetland and aquatic habitats. Although studies indicate that treatments generally have few negative impacts (e.g., Stephens et al. 2012, McIver et al. 2013), treatments will benefit some species and potentially negatively impact others (e.g., Pilliod et al. 2006, Spies et al. 2017, Jain et al. 2012, Manley et al. 2015). The analysis of costs and benefits will also have to consider the likelihood and potential of impacts of high intensity wildfire on those values, which is often difficult to assess (e.g., Utzig et al. 2016, Kennedy and Fontaine 2009). A recent paper by a group of biologists has suggested that even old growth-dependent species like the spotted owl could potentially benefit from fuel treatments and habitat restoration applied at a landscape scale (Stephens et al. 2019).

In general, recommendations to reduce impacts on wildlife habitat recommend the maintenance of snags, coarse woody debris, patches of untreated forest and heterogeneity within the treatment areas as primary strategies to minimize detrimental habitat impacts (e.g., Pilliod et al. 2006, Hesselburg et al. 2016). Natural landscapes in the S WK, where mixed fire regimes were dominant, were always diverse in patch sizes and stand structure, and therefore spatial trade-offs in habitat values are not necessarily contrary to restoration and building resilience.

In addition to potential direct impacts of wildfire on communities and habitats, there are also impacts on ecosystem services, such as supplying wood to the timber industry, domestic and irrigation water supplies, recreational opportunities, visual quality objectives, bio-fuel utilization and other impacts such as air quality from smoke.

A number of studies have evaluated the potential impacts of fuel treatments on watersheds and water supplies (e.g., Leslie 2019), with some suggesting the risk to water security from wildfires is significantly under-estimated (Murphy et al. 2018). One study, looking at the effects of forest fuel treatments within two watersheds in the Sierra Nevada of California, concluded that reduced evapotranspiration resulting from treatment thinning or re-introduced fire could increase water yield by up to 5%, and maybe more in dry years (Roche et al. 2018). Another study looking at the potential costs and benefits of treatment in two watersheds that supply water to Denver, concluded that strategically located fuel treatments were a good investment, as the return on investment garnered through reduced costs of post-fire sediment mitigation exceeded the costs of treatments (Jones et al. 2017). The authors however caution that each watershed will likely have differing factors determining the potential costs and benefits. In the Rio Grande watershed in the southwestern US various stakeholders have joined forces to create a multi-million dollar fund for watershed restoration and resiliency that includes assessment of debris flow hazards associated with wildfire (Tillery and Haas 2016), and extensive strategically located fuel treatment projects. The program is coordinated by The Nature Conservancy, but includes both forest industry and government participants (see https://www.nature.org/riogrande).

11. Other Factors to Consider

Young stands that had been established subsequent to harvesting ***and*** broadcast burning, or wildfire, generally less than 12 m in height and less than 30 years old, had significantly lower fire severity, or didn't burn at all, when encountered by wildfire. In contrast to mature and older stands, those with canopy base heights of <2m and the highest densities had the least fire severity (e.g., Jain and Graham 2007, Lyons-Tinsley and Peterson 2012). The positive outcomes in these stands were generally attributed to low surface fuel levels and higher humidity in the surface fuel zone. However, this condition is temporary, and eventually these stands will grow out of this structural stage and will require fuel treatments in the future to retain their fire resilience.

The size of fuel treatment areas was found to be a significant factor in tree mortality in some cases (e.g., Agee and Skinner 2005, Finney et al. 2005, Prichard and Peterson 2011, Martinson et al. 2003). In general, larger treatment areas were more effective (especially >200 ha), in part due to the less edge per area of treatment. Regardless of treatment and wildfire characteristics, there was tree mortality along the windward edge of treatments, as the wildfire transitioned from an active crownfire to a groundfire. The distance to make this transition varied from a few meters to up to hundreds of meters, depending on the intensity of the fire and the condition of the treated stand. In general the transition was least in treated areas where all four of the basic treatment principles had been followed. The general recommendation flowing from the literature would be to have treated areas be at least 400-450 m wide to create a defensible space surrounding infrastructure, ensuring that fire fighters have sufficient time for deployment and sufficient reduction in fire intensity to allow direct attack (e.g., Kennedy et al. 2019, Safford et al. 2012, Kennedy and Johnson 2014).

Some treatments included provisions for maintaining shrubs and intermediate tree strata to provide habitat for species requiring multi-storied stands (Kennedy and Johnson 2014). These were accommodated by retaining discontinuous untreated patches within the overall treatment area. When the treatment area was burned by the high intensity 2011 Wallow fire, the treatment was still effective in reducing the crown fire in untreated areas to a ground fire, and providing protection to the nearby community. However, the wildlife patches burned with higher intensity that the surrounding treated areas. Similar untreated patches could also be used to maintain key wildlife trees, snags or riparian habitats within treatment areas. Where desirable to maintain a significant number of these treatment reserves, it may be advisable to enlarge the gross treatment area, or at least the width of the treatment area.

Numerous articles also commented that fuel treatments are only one tool in protecting infrastructure from wildfire. FireSmart treatments that reduce the likelihood of structural ignitions are equally, if not more important. Although fuel treatments may reduce fire intensity and the risk of spotting, fire brands can still be carried distances well-beyond treatment zones. Some of the wildfires described in the articles noted here had spotting distances of over 4 km.

There has been significant speculation about the role of mortality caused by insect and disease attacks on the extent and intensity of wildfires. Hicke et al. (2012) provide an excellent summary of modeling and wildfire experiences with mountain pine beetle affected areas. The article indicates what affect a mortality event may have on wildfire depends on the age of the event at the time of the wildfire. Red stage attack is likely most dangerous for active crownfires; however, grey stages may provide increased surface fuels for increased groundfire intensities. A number of the retrospective studies noted in this project found that beetle attacks did not significantly change fire impacts, or had mixed results (e.g., Prichard and Peterson 2010). Some studies indicate that fuel treatments combined with prescribed fire can in fact reduce the risk of subsequent beetle attack mortality in Py and Fd, when compared to untreated or thinned-only treatments (e.g., Prichard and Kennedy 2012).

12. Treatment Planning and Public Participation

Application of fuel treatments in areas adjacent to communities will require extensive public education, public participation and careful consideration of impacts on other resource values (e.g., Ostero et al. 2018, Koch et al. 2016). There is also a need for consideration of smoke management and its impacts on human health. To add to the complexity, recent papers point out that definitions of resilience and risk management have different connotations to those in the natural resource field, from those in the social science and public realms (Higuera et al. 2019, Sherry et al. 2019).

Most practitioners recognize the need to avoid considering fuel treatments in isolation, but rather emphasize the need to incorporate fuel treatment planning into an integrated planning process. Fuel treatments should be seen as another objective that must be coordinated with the whole suite of resource management objectives, including ecosystem restoration, climate change resilience, habitat management, timber harvesting, watershed management, air quality, access management, erosion control, etc. (e.g., Stockman et al. 2010). Appendix 3 provides a schematic planning outline that demonstrates one approach to incorporating fuel management into the broader context of landscape and ecosystem planning.

Different classes of landowners and varying land management objectives can also influence the likelihood that fuel treatments will be undertaken, or how they will be undertaken (e.g., Charnley et al. 2017, Higuera et al. 2019, Spies et al. 2018). Although the complexity of land ownership is likely less of an issue in BC than in the US, there are still tenure and ownership complexities that need to be resolved. For example in the WUI surrounding Nelson there are residential landowners, industrial forestry owners, municipal government owners, industrial forest tenure holders, commercial recreational tenure holders, water licensees, and Crown land managed by both Provincial Parks and the MoFLNRORD. There is a necessity for involving various levels of government, a range of stakeholders, and a wide cross-section of the public to guarantee an effective outcome.

Some general principles to keep in mind ï potential ñkeys to successò

- Treatment units are located and designed as components of a landscape and regional wildfire plan
- Treatment units have clear objectives ï including objectives for other values (heterogeneity within the treatment units has been considered
- Removal of surface fuels and ladder fuels are emphasized; overstory retention balances crown fire risk, potential wind increases and regeneration rates
- Treatment unitsô layout, size and shape are consistent with the objectives (and potentially consistent with the use of prescribed fire)
- Treatment prescriptions include a feasible and effective maintenance plan (required frequency will depend on ecosystem type, treatment, canopy closure, aspect, shrub/herb/tree regeneration)
- All stakeholders and affected parties are openly and transparently consulted

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References

Agee, J.K. 1996. The influence of forest structure on fire behavior. In: Proceedings, 17th Annual Forest Vegetation Management Conference, Redding, CA. January 16-18, 1996: 52-68.

Agee, J.K. and C.N. Skinner. 2005. Basic principles of forest fuel reduction treatments. For. Ecol. Manage. 211(1):83ï 96. doi:10.1016/j. online: www.treesearch/pubs/36541

Ager, A. A., A. M. G. Barros, H. K. Preisler, M. A. Day, T. A. Spies, J. D. Bailey, and J. P. Bolte. 2017. Effects of accelerated wildfire on future fire regimes and implications for the United States federal fire policy. Ecology and Society 22(4):12. https://doi.org/10.5751/ES-09680-220412

Ager, A., N. Vaillant, M. Finney. 2010. A comparison of landscape fuel treatment strategies to mitigate wildland fire risk in the urban interface and preserve old forest structure. Forest Ecology and Management. 259: 1556ï 1570.

Belote, R.T., A. Larson, M. Dietz. 2015. Tree survival scales to community-level effects following mixed-severity fire in a mixed-conifer forest. For. Ecol. and Mngmt. 353(2015) DOI: 10.1016/j.foreco.2015.05.033

Barros, A. M. G., A. A. Ager, M. A. Day, H. K. Preisler, T. A. Spies, E. White, R. Pabst, K. A. Olsen, E. Platt, J. D. Bailey, and J. P. Bolte. 2017. Spatiotemporal dynamics of simulated wildfire, forest management, and forest succession in central Oregon, USA. Ecology and Society 22(1):24. https://doi.org/10.5751/ES-08917-220124

BC Wildfire Service. 2018. Provincial Strategic Threat Analysis: 2017 Update. Report produced for BC MoFKLNRORD.

Campbell, J. L., and A. A. Ager. 2013. Forest wildfire, fuel reduction treatments, and landscape carbon stocks: a sensitivity analysis. Journal of Environmental Management 121:124ï 132.

Campbell, J.L, Harmon, M.E,, Mitchell, S.R., 2012. Can fuel reduction treatments really increase forest carbon sequestration by reducing future fire emissions? Frontiers in Ecology and the Environment 10 (2), 83-90.

Carlson, C. H., S. Dobrowski, and H. Safford. 2012. Variation in tree mortality and regeneration affect forest carbon recovery following fuel treatments and wildfire in the Lake Tahoe Basin, California, USA. Carbon Balance and Mgmt. 7(1)7. http://www.cbmjournal.com/content/7/1/7

Charnley, S., T. A. Spies, A. M.G. Barros, E. M. White, and K. A. Olsen. 2017. Diversity in forest management to reduce wildfire losses: implications for resilience. Ecology and Society 22(1):22. https://doi.org/10.5751/ES-08753-220122

Chung, W. 2015. Optimizing Fuel Treatments to Reduce Wildland Fire Risk. Curr Forestry Rep (2015) 1:44ï 51

Churchill, D.J., Larson, A.J., Dahlgreen, M.C., Franklin, J.F., Hessburg, P.F., Lutz, J.A. 2013. Restoring forest resilience: from reference spatial patterns to silvicultural prescriptions and monitoring. For. Ecol. Manage. 291, 442ï 457. (abstract only)

Collins, B.M., J. Miller, A. Thode, M. Kelly, J. Wagtendonk, S. Stephens. 2009. Interactions among Wildland Fires in a long-established Sierra Nevada Natural Fire Area. Ecosystems 2008, 12:114ï 128.

Daniels, L., J. Cochrane & R. Gray. 2007. Mixed-severity fire regimes: regional analysis of the impacts of climate on fire frequency in the Rocky Mountain Forest District. Report to Forest Investment Account of British Columbia and Parks Canada Agency.

Fernandes, P. M., and H. S. Botelho. 2003. A review of prescribed burning effectiveness in fire hazard reduction. International Journal of Wildland Fire 12(2):117-128. http://dx.doi.org/10.1071/wf02042

Fialko, K. 2018. Conifer regeneration and fuels treatment longevity in dry mixed conifer forests of the Colorado front range. MS Thesis. Colorado State University, Fort Collins, Colorado. 40pp.

Filmon, G. 2004. Firestorm 2003 ï Provincial Review. Report completed for the Prov. of BC.

Finney, M.A., McHugh, C.W., and Grenfell, I.C. 2005. Stand- and landscape-level effects of prescribed burning on two Arizona wildfires. Canadian Journal of Forest Research 35: 1714-1722.

Forest Practices Board. 2015. Fuel Management in the Wildland Urban Interface ï Update. Special Investigation Report. FPB/SIR/43.

Fule, P.Z., W. Covington, H. Smith, J. Springer, T. Heinlein, K. Huisinga, M. Moore. 2002. Comparing ecological restoration alternatives: Grand Canyon, Arizona. For Ecol and Mngmt 170(2002):19ï 41.

Forest Service, Rocky Mountain Research Station. 36 p. online: www.treesearch/pubs/33178.Graham, R., N. Finney, C. McHugh, J. Cohen, D. Calkin, R. Stratton, L. Bradshaw, N. Nikolov. 2012. Fourmile Canyon Fire Findings. Gen. Tech. Rep. RMRS-GTR-289. Fort Collins, CO: USDA FS, Rocky Mtn Res Stn. 110p.

Graham, R.T., T. Jain, M. Loseke. 2009. Fuel treatments, fire suppression, and their interaction with wildfire and its effects: the Warm Lake experience during the Cascade Complex of wildfires in central Idaho, 2007. Gen. Tech. Rep. RMRS-GTR-229. Fort Collins, CO: USDA FS.

Graham, R.T., S. McCaffrey, T. Jain (tech. eds.). 2004. Science basis for changing forest structure to modify wildfire behavior and severity. Gen. Tech. Rep. RMRS-GTR-120. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mtn Res Stn. 43p.

Greene, G. A. (2011). Historical fire regime of the Darkwoods: Quantifying the past to plan for the future. Geography. Vancouver, B.C., University of British Columbia, MSc Thesis, 115 pp.

Halofsky, J. S., D. C. Donato, J. F. Franklin, J. E. Halofsky, D. L. Peterson, and B. J. Harvey. 2018. The nature of the beast: examining climate adaptation options in forests with stand-replacing fire regimes. Ecosphere 9(3):e02140.10.1002/ecs2.2140.

Haugo, R., Zanger, C., DeMeo, T., Ringo, C., Shlisky, A., Blankenship, K., Simpson, M., Mellen-McLean, K., Kertis, J., Stern, M., 2015. A new approach to evaluate forest structure restoration needs across Oregon and Washington, USA. For. Ecol. Manage. 335, 37ï 50.

Hessburg, P., D. Churchill, A. Larson, R. Haugo, C. Miller, T. Spies, M. North, N. Povak, R. Belote, P. Singleton, W. Gaines, R. Keane, G. Aplet, S. Stephens, P. Morgan, P. Bisson, B. Rieman, R. Salter, G. Reeves. 2015. Restoring fire-prone Inland Pacific landscapes: seven core principles. Landscape Ecology. 30(10):1805-1835.

Hessburg, P.F., Spies, T.A., Perry, D.A., Skinner, C.N., Taylor, A.H., Brown, P.M., Stephens, S.L., Larson, A.J., Churchill, D.J., Povak, N.A., Singleton, P.H., McComb, B., Zielinski, W.J., Collins, B.M., Salter, R.B., Keane, J.J., Franklin, J.F., Riegel, G. 2016. Tamm Review: Management of mixed-severity fire regime forests in Oregon, Washington and Northern California. Forest Ecology and Management 366, 221ï 250.

Hicke, J.A., M. Johnson, J. Hayes and H. Preisler. 2012. Effects of bark beetle-caused tree mortality on wildfire. Forest Ecology and Management 271:81-90.

Higuera, P.E., A. Metcalf, C. Miller, B. Buma, D. McWethy, E. Metcalf, Z. Ratajczak, C. Nelson, B. Chaffin, R. Stedman, S. McCaffrey, T. Schoennagel, B. Harvey, S. Hood, C. Schultz, A. Black, D. Campbell, J. Haggerty, R. Keane, M. Krawchuk, J. Kulig, R. Rafferty, A. Virapongse. 2019. Integrating subjective and objective dimensions of resilience in fire-prone landscapes. BioScience. 69(5): 379-388.

Holt, R.F., G. Utzig, H. Pinnell and C. Pearce. 2012. Vulnerability, Resilience and Climate Change: Adaptation Potential for Ecosystems and Their Management in the West Kootenay ï Summary Report. Report #1 for the West Kootenay Climate Vulnerability and Resilience Project. Available at www.kootenayresilience.org

Hurteau, M.D., S. LIang, K. MartIn, M. North, G. Koch and B. Hungate. 2016. Restoring forest structure and process stabilizes forest carbon in wildfire-prone southwestern ponderosa pine forests. Ecol ApplIns 26(2):382ï 391.

Hurteau, M., M. North, G. Koch, B. Hungate. 2019. Managing for disturbance stabilizes forest carbon. PNAS 116(21):10193ï 10195.

Jain, T., M. Battaglia, H-S. Han, R. Graham, C. Keyes, J. Fried, J. Sandquist. 2012. A comprehensive guide to fuel management practices for dry mixed conifer forests in the NW US. Gen. Tech. Rep. RMRS-GTR-292. Fort Collins, CO: USDA FS, Rocky Mountain Research Station. 331 p.

Jain, T.B. and R.T. Graham. 2007. The relation between tree burn severity and forest structure in the Rocky Mountains. In: Powers, Robert, tech. ed. Restoring fire-adapted forested ecosystems: proceedings of the 2005 national silviculture workshop; 2005 June 6-10; Lake Tahoe, CA. Gen. Tech. Rep. PSW-GTR-203. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: 213-250. online: www.treesearch.fs.fed.us/pubs/25904.

Jandl, R., R. Spathelf, A. Bolte, C. Prescott. 2019. Forest adaptation to climate change ï Is non-management and option? Annals of For. Science (2019)76:48. https://doi.org/10.1007/s13595-019-0827-x

Johnson, M.C., D. Peterson, C. Raymond. 2007. Guide to fuel treatments in dry forests of the Western United States: assessing forest structure and fire hazard. Gen. Tech. Rep. PNW-GTR-686. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 322p.

Johnson, M.C.; Kennedy, M.C.; Peterson, D.L. 2011. Simulating fuel treatment effects in dry forests of the Western United States: testing the principles of a fire-safe forest. Canadian Journal of Forest Research. 41(6): 1018ï 1030.

Jones, K.W., J. Cannon, F. Saavedra, S. Kampf, R. Addington, A. Cheng, L. MacDonald, C. Wilson, B. Wolk. 2017. Return on investment from fuel treatments to reduce severe wildfire and erosion in a watershed investment program in Colorado. J of Env.Mgmt. 198(2017):66-77.

Keane, R.E., Hessburg, P.F., Landres, P.B., Swanson, F.J., 2009. The use of historical range and variability (HRV) in landscape management. For. Ecol. Manage. 258, 1025ï 1037. http://dx.doi.org/10.1016/j.foreco.2009.05.035.

Keller, P. 2011. How Fuel Treatments Saved Homes from the 2011 Wallow Fire. Wildland Fire Lessons Learned Center. Public Pamphlet.

Kennedy, P.L. and J. Fontaine. 2009. Synthesis of knowledge on the effects of fire and fire surrogates on wildlife in U.S. dry forests. Corvallis, OR: Oregon State University, Agricultural Experiment Station. 132 p.

Kennedy, M. C., M. C. Johnson, K. Fallon, and D. Mayer. 2019. How big is enough? Vegetation structure impacts effective fuel treatment width and forest resiliency. Ecosphere 10(2):e02573. 10.1002/ecs2.2573

Kennedy, M.C. and M.C. Johnson. 2014. Fuel treatment prescriptions alter spatial patterns of fire severity around the wildland-urban interface during the Wallow Fire, Arizona, USA. Forest Ecology and Management. 318: 122ï 132.

Keysera, A.R. and A. L. Westerling. 2019. Predicting increasing high severity area burned for three forested regions in the western United States using extreme value theory Forest Ecology and Management. Vol. 432, 15 January 2019, Pages 694-706.

Kirchmeier-Young, M. C., Gillett, N. P., Zwiers, F. W., Cannon, A. J., & Anslow, F. S. (2019). Attribution of the influence of human-induced climate change on an extreme fire season. Earthɒs Future, 7. https://doi.org/10.1029/2018EF001050

Koch, G., A. Ager, J. Kline, P. Fischer. 2016. Polishing the prism: improving wildfire mitigation planning by coupling landscape and social dimensions. Science Findings 189. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 5 p.

Krofcheck, D. J., Hurteau, M. D., Scheller, R. M., and Loudermilk, E. L.., 2017. Restoring surface fire stabilizes forest carbon under extreme fire weather in the Sierra Nevada. Ecosphere 8, (1).

Leslie, J., 2019. For a Warming World, A New Strategy for Protecting Watersheds. Yale Environment 360. Accessed online 6/30/2019 at: https://e360.yale.edu/features/why-restoring-watersheds-is-a-new-priority-in-a-warming-world

Lyons-Tinsley, C. and D. Peterson. 2012. Surface fuel treatments in young, regenerating stands affect wildfire severity in a mixed conifer forest, eastside Cascade Range, Washington, USA. Forest Ecology and Management. 270:117-125.

Manley, P.N., G. Traynor, A. White. 2015. Effects of Forest Biomass Fuel Reduction Treatments on Birds and Small Mammal Communities in the Sierra Nevada: Research to Inform Forest Biomass Energy Practices. California Energy Commission. Publication number: CEC-500-2016-021.

Martinson, E. J. and P.N. Omi. 2013. Fuel treatments and fire severity: A meta-analysis. Res. Pap. RMRS-RP-103WWW. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 38 p.

Martinson, E., P. Omi, W. Shepperd. 2003. Effects of Fuel Treatments on Fire Severity in Graham, R., Technical Editor. 2003. Hayman Fire Case Study. Gen. Tech. Rep. RMRSGTR- 114. Ogden, UT: USDA FS, Rocky Mountain Research Station. 396p.

Martinson, E.J. and P. N. Omi. 2003. Performance of Fuel Treatments Subjected to Wildfires *in* Omi, P. N. and L.A. Joyce, technical editors. 2003. Fire, fuel treatments, and ecological restoration: Conference proceedings; 2002 16-18 April; Fort Collins, CO. Proceedings RMRS-P-29. Fort Collins, CO: USDA-FS, Rocky Mountain Research Station. pp.7-14.

McIver, J.D., S. Stephens, J. Agee, J. Barbour, R. Boerner, C. Edminster, K. Erickson, K. Farris, C. Fettig, C. Fiedler, S. Haase, S. Hart, J. Keeley, E. Knapp, J. Lehmkuhl, J. Moghaddas, W. Otrosina, K. Outcalt, D. Schwilk, C. Skinner, T. Waldrop, C. Weatherspoon, D. Yaussy, A. Youngblood and S. Zack. 2013. Ecological effects of alternative fuel-reduction treatments: highlights of the National Fire and Fire Surrogate study (FFS). Int. J of Wildland Fire 2013(22):63ï 82. http://dx.doi.org/10.1071/WF11130

Meigs, G. W., Donato, D. C., Campbell, J. L., Martin, J. G., and Law, B. E., 2009. Forest fire impacts on carbon uptake, storage, and emission: The role of burn severity in the Eastern Cascades, Oregon. Ecosystems, 12(8), 1246ï 1267.

Moghaddas, J. J., and L. Craggs. 2007. A fuel treatment reduces potential fire severity and increases suppression efficiency in a Sierran mixed conifer forest. International Journal of Wildland Fire 16:673ï 678

Moghaddas, J.J., G. Roller, J. Long, D. Saah, M. Moritz, D. Stark, D. Schmidt, T. Buchholz, T. Freed, E. Alvey, and J. Gunn. 2018. Fuel Treatment for Forest Resilience and Climate Mitigations: A Critical Review for Coniferous Forests of the Sierra Nevada, Southern Cascade, Coast, Klamath, and Transverse Ranges. California Natural Resources Agency. Publication number: CCCA4-CNRA-2018-017.

Murphy, B. P., Yocom, L. L., & Belmont, P. 2018. Beyond the 1984 perspective: Narrow focus on modern wildfire trends underestimates future risks to water security. Earth's Future, 6, 1492ï 1497. https://doi.org/10.1029/2018EF001006

Nesbitt, J. H. (2010). Quantifying forest fire variability using tree rings. Nelson British Columbia 1700-Present. Department of Geography. Vancouver, B.C., University of British Columbia. MSc Thesis, 112 pp.

North, M., J. Stevens, D. Green, M. Coppolett, E. Knapp, A. Latimer, C. Restaino, R. Tompkins, K. Welch, R. York, D. Young, J. Axelson, T. Buckley, B. Estes, R. Hager, J. Long, M. Meyer, S. Ostoja, H. Safford, K. Shive, C. Tubbesing, H. Vice, D. Walsh, C. Werner, P. Wyrsch. 2018. Tamm Review: Reforestation for resilience in dry western U.S. forests. Forest Ecology and Management 432(2019):209ï 224

Ohlson, D.W., T. Berry, R. Gray, B. Blackwell, B. Hawkes. 2006. Multi-attribute evaluation of landscape-level fuel management to reduce wildfire risk Forest Policy and Economics 8:824ï 837.

Omi, P. N. and L.A. Joyce, technical editors. 2003. Fire, fuel treatments, and ecological restoration: Conference proceedings; 2002 16-18 April; Fort Collins, CO. Proceedings RMRS-P-29. Fort Collins, CO: USDA-FS, Rocky Mountain Research Station. 475p.

Otero I, M. Castellnou, I. Gonza´lez, E. Arilla, L. Castell, J. Castellvĕ, F. Sa´nchez, J. Nielsen. 2018. Democratizing wildfire strategies. Do you realize what it means? Insights from a participatory process in the Montseny region (Catalonia, Spain). PLoS ONE 13(10): e0204806. https://doi.org/10.1371/journal.pone.0204806

Parks, S. A., C. Miller, J. T. Abatzoglou, L. M. Holsinger, M.-A. Parisien, and S. Z. Dobrowski. 2016. How will climate change affect wildland fire severity in the western US? Environmental Research Letters 11:035002

Peterson, D.L., Johnson, M.C., Agee, J.K., Jain, T.B., McKenzie, D. and Reinhardt, E.R. 2005. Forest structure and fire hazard in dry forests of the western United States. PNW-GTR-628. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Petrakis, R.E., M. Villarreal, Z. Wu, R. Hetzler, B. Middleton, L. Norman. Evaluating and monitoring forest fuel treatments using remote sensing applications in Arizona, U.S.A. For Ecol and Mngmt 413(2018)48ï 61

Pilliod, David S.; Bull, Evelyn L.; Hayes, Jane L.; Wales, Barbara C. 2006. Wildlife and invertebrate response to fuel reduction treatments in dry coniferous forests of the Western United States: a synthesis. Gen. Tech. Rep. RMRS-GTR-173. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 34 p.

Pollet, J. and P. Omi. 2002. Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. International Journal of Wildland Fire. 11(1):1-10. (abstract only)

Prichard, S.J., P. Hessburg, R. Gray, N. Povak, R. Salter, C. Stevens-Rumann, P. Morgan. 2018. Evaluating the influence of prior burn mosaics on subsequent wildfire behavior, severity, and fire management options. Final Report for JFSP PROJECT ID: 14_1_02_30. Project website: https://depts.washington.edu/nwfire/reburn.

Prichard, S. J. and D. L. Peterson. 2010. Do fuel treatments reduce fire severity? Evaluating treatment effectiveness in the 2006 Tripod Complex fires Final Report to the Joint Fire Science Program Project Number: 07-1-2-13. http://www.fs.fed.us/pnw/fera/research/treatment/tripod/index.shtml

Prichard, S. J. and D. L. Peterson. 2011. Landscape analysis of fuel treatment longevity and effectiveness in the 2006 Tripod Complex Fires Final Report to the Joint Fire Science Program Project Number: 09-1-01-19. http://www.fs.fed.us/pnw/fera/research/treatment/tripod/index.shtml

Prichard, S.J. and Kennedy, M.C. 2012. Fuel treatment effects on post-fire tree mortality and beetle attack in dry mixed conifer forests, Washington State, USA. International Journal of Wildland Fire 21:1004ï 1013.

Prichard, S.J., Peterson, D.L., and Jacobson, K., 2010. Fuel treatments reduce the severity of wildfire effects in dry mixed conifer forest, Washington, USA. Canadian Journal of Forest Research 40: 1615ï 1626.

Raymond, C., Peterson, D., 2005. Fuel treatments alter the effects of wildfire in a mixed-evergreen forest, Oregon, USA. Can. J. For. Res. 35, 2981ï 2995. http://dx.doi.org/10.1139/X05-206

Reinhardt, E.D., R. Keane, D. Calkin, J. Cohen. 2008. Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. Forest Ecology and Management. 256(12): 1997-2006. online: https://www.fs.usda.gov/treesearch/pubs/31574

Restaino, C., Young, D. Estes, B., Gross, S., Wuenschel, A. Meyer, Safford, H. 2019. Forest structure and climate mediate drought-induced tree mortality in forests of the Sierra Nevada, USA. Ecol Applns. 29(40). https://doi.org/10.1002/eap.1902 (abstract only).

Ritchie, M.W., Skinner, C.N., and Hamilton, T.A. 2007. Probability of tree survival after wildfire in an interior pine forest of northern California: effects of thinning and prescribed fire. Forest Ecology and Management 247:200-208.

Roche, J., M. Goulden, R. Bales. 2018. Estimating evapotranspiration change due to forest treatment and fire at the basin scale in the Sierra Nevada, California. Ecohydrology. 2018;11:e1978. https://doi.org/10.1002/eco.1978

Safford, H.D., D. Schmidt and C. Carlson. 2009. Effects of fuel treatments on fire severity in an area of wildlandï urban interface, Angora Fire, Lake Tahoe Basin, California. For Ecol and Mngmt 258: 773-787.

Safford, H.D., J. Stevens, K. Merriam, M. Meyer, A. Latimer. 2012. Fuel treatment effectiveness in California yellow pine and mixed conifer forests. For. Ecol. Manage. 274, 17ï 28. http://dx.doi.org/10.1016/j.foreco.2012.02.013

Schoennagel, T,, J. Balch, H. Brenkert-Smith, P. Dennison, B. Harvey, M. Krawchuk, N. Mietkiewicz, P. Morgan, M. Moritz, R. Rasker, M. Turner. C. Whitlock. 2017. Adapt to more wildfire in western North American forests as climate changes. PNAS 114(18):4582-4590.

Schroeder, D. 2010. Fire behaviour in thinned jack pine: two case studies in FireSmart treatments in Canadaõs NW Territories. FPInnovations Advantage 12(7)

Scott, J.H. and Reinhardt, E.D. 2001. Assessing crown fire potential by linking models of surface and crown fire behavior. Res. Pap. RMRS-RP-29. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 59 p.

Sherry, J., T. Nealeb, T. McGee, M. Sharpe. 2019. Rethinking the maps: A case study of knowledge incorporation in Canadian wildfire risk management and planning. J of Env Mgmt 234(2019):494ï 502.

Skinner, C.N., Ritchie, M.W., Hamilton, T., Symons, J. 2004. Effects of thinning and prescribed fire on wildfire severity: the Cone Fire, Blacks Mountain Experimental Forest. In: Proceedings of the 25th Annual Forest Vegetation Management Conference, January 20ï 24, 2004. Redding, CA. pp80-91.

Spies, T. A., R. M. Scheller, and J. P. Bolte. 2018. Adaptation in fire-prone landscapes: interactions of policies, management, wildfire, and social networks in Oregon, USA. Ecology and Society 23(2):11. https://doi.org/10.5751/ES-10079-230211

Spies, T. A., E. White, A. Ager, J. D. Kline, J. P. Bolte, E. K. Platt, K. A. Olsen, R. J. Pabst, A. M.G. Barros, J. D. Bailey, S. Charnley, A. T. Morzillo, J. Koch, M. M. Steen-Adams, P. H. Singleton, J. Sulzman, C. Schwartz, and B. Csuti. 2017. Using an agent-based model to examine forest management outcomes in a fire-prone landscape in Oregon, USA. Ecology and Society 22(1):25. https://doi.org/10.5751/ES-08841-220125

Stephens, S.L., L. Kobziar, B. Collins, R. Davis, P. Fulé, W. Gaines, J. Ganey, J. Guldin, P. Hessburg, K. Hiers, S. Hoagland, J. Keane, R. Masters, A. McKellar, W. Montague, M. North, T. Spies. 2019. Is fire ñfor the birdsò? How two rare species influence fire management across the US. Frontiers in Ecol and the Env. https://doi.org/10.1002/fee.2076 (or see summary at https://www.sciencedaily.com/releases/2019/07/190702160114.htm).

Stephens, S.L., J. McIver, R. Boerner, C. Fettig, J. Fontaine, B. Hartsough, P. Kennedy, and D. Schwilk. 2012. The Effects of Forest Fuel-Reduction Treatments in the United States. BioScience 62(6) doi:10.1525/bio.2012.62.6.6

Stevens-Rumann, C., S. Prichard, E.Strand, P. Morgan. 2016. Prior wildfires influence burn severity of subsequent large fires. Can. J. For. Res. 46:1375ï 1385 dx.doi.org/10.1139/cjfr-2016-0185.

Stevens, J. T., B. M. Collins, J. W. Long, M. P. North, S. J. Prichard, L. W. Tarnay, and A. M. White. 2016. Evaluating potential trade-offs among fuel treatment strategies in mixed-conifer forests of the Sierra Nevada. Ecosphere 7(9):e01445. 10.1002/ecs2.1445

Stockmann, K. D., K. Hyde, J. Jones, D. Loeffler, R. Silverstein. 2010. Integrating fuel treatment into ecosystem management: a proposed project planning process. International Journal of Wildland Fire 19(6): 725-736. online: www.treesearch/pubs/36295

Symons, J., D. Fairbanks, C. Skinner. 2008. Influences of stand structure and fuel treatments on wildfire severity at Blacks Mountain Experimental Forest, northeastern California. The California Geographer 48:1-23.

Tempel, D. J., R. J. Gutie´rrez, J. J. Battles, D. L. Fry, Y. Su, Q. Guo, M. J. Reetz, S. A. Whitmore, G. M. Jones, B. M. Collins, S. L. Stephens, M. Kelly, W. J. Berigan, and M. Z. Peery. 2015. Evaluating short- and long-term impacts of fuels treatments and simulated wildfire on an old-forest species. Ecosphere 6(12):261. http://dx.doi.org/10.1890/ES15-00234.1

Tepley, A.J., Swanson, F.J., Spies, T.A. 2013. Fire-mediated pathways of stand development in Douglas-fir/western hemlock forests of the Pacific Northwest, USA. Ecology 94:1729ï 1743.

Thompson, J.R. and T. Spies. 2009. Vegetation and weather explain variation in crown damage within a large mixed severity wildfire. Forest Ecology and Management 258(2009):1684ï 1694.

Thompson, J.R., T. Spies and K. Olsen. 2011. Canopy damage to conifer plantations within a large mixed-severity wildfire varies with stand age. Forest Ecology and Management 258(2011):355-360.

Thompson M., K. Riley, D. Loeffler and J. Haas. 2017. Modeling Fuel Treatment Leverage: Encounter Rates, Risk Reduction, and Suppression Cost Impacts. Forests 8(469): ; doi:10.3390/f8120469

Tillery, A.C., and Haas, J.R., 2016, Potential post-wildfire debris-flow hazardsð A pre-wildfire evaluation for the Jemez Mountains, north-central New Mexico: U.S. Geological Survey Scientific-Investigations Report 2016-5101, 27 p., http://dx.doi.org/10.3133/sir20165101.

Utzig, G., R.F. Holt, and M.M. Machmer. 2016. Darkwoods Conservation Property: Climate Change Vulnerability and Fire Management Planning. Final Report. Nature Conservancy of Canada, Nelson, BC. 40 pp.

Utzig, G. 2012. Ecosystem and Tree Species Bioclimate Envelope Modeling for the West Kootenays. Report #5 from the West Kootenay Climate Vulnerability and Resilience Project. Available at: www.kootenayresilience.org

Utzig, G., J. Boulanger and R.F. Holt. 2011. Climate Change and Area Burned: Projections for the West Kootenays. Report #4 from the West Kootenay Climate Vulnerability and Resilience Project. Available at: www.kootenayresilience.org

Vaillant, N.M., and E. Reinhardt. 2017. An evaluation of the Forest Service hazardous fuels treatment programð Are we treating enough to promote resiliency or reduce hazard? Journal of Forestry. 115(4):300ï 308.

Waltz, A., M. Stoddard, E. Kalies, J. Springer, D. Huffman, A. Meador. 2014. Effectiveness of fuel reduction treatments: Assessing metrics of forest resiliency and wildfire severity after the Wallow Fire AZ. Forest Ecology and Management 334(2014):43ï 52

White, R., M. Johnson, N. Vaillant, J. Fried. 2018. Fuel treatments: Are we doing enough? Science Update 25. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 15 p. Available at: https://www.fs.usda.gov/treesearch/pubs/57406

Wimberly, M.C., Cochrane, M.A., Baer, A.D., and Pabst, K. 2009. Assessing fuel treatment effectiveness using satellite imagery and spatial statistics. Ecological Applications 19: 1377-1384.

Appendix 1: Summary of Key References

Table A1-1. Summary of post-wildfire studies assessing the effectiveness of fuel treatments.

Author/Article	Study Area	Treatments	Wildfire	Outcomes	Comments
Agee and Skinner 2005	Tyee Fire WA 1994 Wenatchee NF mixed conifer of 60 yr second growth	5-20 ha treatments – details of trtmt not specified Goman Peak fuelbreak 1970s thinning from below to about 10m2/ha, pruning to 3m, pile and burn thinning caused faster growth/ bigger trees in fuelbreak	50,000 ha	crown scorch from above and then ground fire under – many trees later died from “sandwich scorching” Goman fuelbreak: stand-replacing crown fire in adjacent untreated – windward and leeward – surface fire in fuelbreak – still significant mortality due to scorching	treatment areas need to be bigger – to minimize edge effect bigger trees are better good photo Fig 7
Agee and Skinner 2005	Megram Fire NW CA 1999 Fd dominated mixed-conifer forest	250m wide fuelbreaks some only had surface and ladder fuels treated with residual canopy cover maintained at >60-70% of pre-treatment	12,000 ha of windthrow from 1995-96 no suppression in area of fuel treatments	stand-replacing crown fire in adjacent untreated – windward and leeward – surface fire in treatments minimal mortality in treatments, some canopy scorch on windward sides	reductions in canopy bulk density are not always needed to reduce fire severity” photo Fig 8
Agee and Skinner 2005	Hayman Fire, CO (NW of Denver) 2002 Finney 2002	not specified	50,000 ha (25,000 in one day) some winds of 135kph and fuels <6% moisture	treatments reduced severity – except when: extreme winds >10-15 yrs old < 100 ha “timber stand improvement” areas wo/ fuel trtmts burned with higher severity than untreated	
Agee and Skinner 2005 and	Cone Fire CA 2002 Py dominated stands Oliver 2000	three 100 ha areas 4 trtmts Leave largest trees (HiD) 5yrs old	800 ha crown fire warm with 6-16 km/hr winds with	thinned and burned – fire entered and died Fire burned further in HiD than	good photo fig 9

Author/Article	Study Area	Treatments	Wildfire	Outcomes	Comments
Skinner et al. 2004 See also Richie et al. 2007; Symons et al. 2008		(~21m2/ha, ~30% CC) Thin below & above (LoD)- intermediate dia trees well-spaced – 5yrs and 2yrs old (~9.2 m2/ha, 15-20% CC) half w/ surface fuels trtd w/ prescribed burning half w/ lop and scatter	gusts to 34 km/hr	LoD due to more litterfall under big trees lop and scatter – surface fire with some mortality due to scorching	
Agee and Skinner 2005	Hayfork Fires CA 1987 Fd dominated mixed-conifer forest Weatherspoon and Skinner 1995	Diameter limit removal of large stems; lop and scatter or under-burning not fire treatments per se	20 separate fires for total of about 20,000 ha	Natural untreated had best survival Under-burned similar to natural; lop and scatter was worse	The wrong treatment can make it worse – i.e. thinning without slash treatments
Belote et al. 2015	Helen and Little Salmon Creek fires 2000 and 2003; sampled 8-12 yrs post fire Little Flathead River in NW MT Lw, Fd, Se, Bl, Pl (minor Py and At) – likely MS BEC zone?	No treatment	Mixed severity fire – sampled across severities	Following wildfire, mortality lowest among large diameter larch; mortality was highest among Bl and Pl (~95-100%), with Se slightly better, and Fd only slightly better than Se (~80; 75%) – Lw was best by far (~35%)	Need to consider fire resistant spp and potential pest issues; high Fd mortality was likely the result of post-fire attack by Dfir beetle
Carlson et al. 2012 Focus on carbon pools	Angora fire 2007 Lake Tahoe, Sierra Nevada CA 1800-2310m elev. Mixed coniferous: Jeffrey pine, white fir lower slopes; red fir upper slopes some Pl, At and incense cedar; some chaparral – no fire since 1882	182 ha treated for fuels 1996-2006 pre-commercial hand thin, commercial thin and salvage of standing dead residual BA 36.7m2/ha for trees >25.4cm DBH; retain snags >76.2 cm; hand thinning left trees >35.6 cm and bole spacing of 6.1 m pile and burn slash and sound CWD biomass reduction from 57.9 tons/ha to 11 tons removed ~36% of above-ground biomass	1106 ha of forest early season (June) after record drought 8 days – 2/3s in first day	mortality (% BA) in untreated was ~85%+; in treated 31% (~5-50%) most trees died first year, some in 2nd and 3rd years 3 yrs after fire: treated retained 55% of aboveground C as live trees untreated only 6.5% trtd stands have lower seedling densities than untrtd (794.74 vs. 2765.14 natural seedlings	trtmts effectively reduced fire severity and tree mortality treated stands will recover pre-wildfire carbon stocks 10-35 yrs faster than untreated

Author/Article	Study Area	Treatments	Wildfire	Outcomes	Comments
	extensive clearcutting in 1890s Before Euroamerican settlement - high frequency/low severity fire regime return intervals: 5–30 years with a mean return interval of ~11 years	13 treated plots and 26 not in fire and 9 trtd and 9 not trtd outside fire		ha-1) three years after fire. However, median rates of regen in trtd stands are higher than those in untrtd (518.93 vs. 0 seedlings ha-1), as 51% of plots in untrtd stands had no natural regen 3 years after fire, vs. only 14% of plots in trtd stands	
Finney et al. 2005	Rodeo and Chediski fires in 2002 Py stands Natural fire interval was likely 2-10 years	Study mainly looked at prescribed burning treatments 0.02 to 22.6 km2 There was also some thinning over time	Relative humidity <10% and wind gusts to 40 and 70kmph Fuel moisture in dead fuels <4%	Treatments definitely decreased fire severity Patches of treatment affected fire at the landscape scale and limited fire growth	Effectiveness in reducing fire severity depended on time since treatment, unit size and number of repeated prescribed burns Larger size allowed for more area away from untreated edge
Graham et al. 2009	Monumental and North Fork Fires 2007 Central Idaho	WUI treatments: prescribed fire in Py and Fd Pl – mechanical trtmts to reduce surface and ladder fuels, thinning to 3-5 m tree spacing; canopy base height increased to 1.5 m by pruning; pile and burn slash Some combined mechanical and burning, some mastication w/ and wo/ burning	Previous winter and spring with only ~50% of normal snow and precip – extreme drought Fuel MC <5%, some to 10% Gusts to 30mph Temps 90-100F	Crews burnt surface fuels in trtmt areas as back fires Spot fires in the treated areas were easily contained by crews Lower fire intensity in trtmt areas allowed crews to work there Some trtmt areas acted as speed bumps to the fire – the “eddy effect”	Average cost <$500/ ha Fire intensity was directly influenced by interactions between wind and topography at the time – layout of trtmts are an important consideration Mortality was reduced in trtmt areas
Graham et al. 2012	Fourmile Canyon Fire 2010 near Boulder CO Fd and Py	Thinning, but without effective surface fuel removal – in some cases piles of slash remained treatment areas small and narrow 250 ha treated 1-7 years previously – no maintenance and some incomplete;	Fast moving high intensity with winds (15mph gusting to 40); extremely low humidity Spotting 0.8 to 1.6km	Treated areas were ineffective Some treated areas with unburned slash piles and abundant ground and ladder fuels due to lack of maintenance burned with more intensity that untreated	Not sure of treatments and how they burned in many cases Ridge crests burned worst, valley bottoms burned less Emphasis on ground and

Author/Article	Study Area	Treatments	Wildfire	Outcomes	Comments
		no burning some narrow along roads to defend escape routes	162 rural homes burnt on 2 days – structural firefighters overwhelmed trying to protect 474 homes	Fire-smarted homes survived best – many homes burnt by low intensity fires	ladder fuels and fire smarting
Kennedy et al. 2019	Bald Fire 2014 Lassen NF NE CA 1000 – 1700 m l to sl volcanic soils Py, Pjeffery, incense cedar, Fd, white fir, (sugar pine gray pine, western juniper, At, Ac and oak) mainly thinned second growth	"Defensible fuel profile zones" – shaded fuelbreak 400-800 m wide additional treatments: underburned 1998-1999 thinned from below to 27.5m2/ha; surface fuels (prescribed fire, pile burns 2001-2) treated 63% density reduction but BA from 22.3m2 to 19.9m2: CC from ~42% to 28% increased crown base height by 165% (~2.5 to ~8)	15,950 ha – July 30 to Aug 6 31oC, RH 13%, wind 14.5 km/hr fuel moisture 2-7%	15 transects going from untrtd to trtd following fire spread; plots every 30 m almost 100% mortality in untrtd 500-600m to significantly reduce crown scorch and bole char ratio	trtmt reduced fire severity needed at least 400 m in this scenario to significantly reduce severity distance into trtd area may have resulted from small residual trees – need big leave trees!
Kennedy and Johnson 2014 see also Waltz et al. 2014	Wallow Fire, AZ 2011 Py, Fd co-doms with white fir, Bl, sw Pw, blue spruce, Se, Gambel oak, locust juniper, mahogany, willow, At AP2 – mostly Abies AP6 – Abies/Fd/Oak/Pinus NU – Oak,Fd,Pinus slope 18-22%	WUI thinning and ground fuels AP2 – 2004 AP6 – 2008 800m from residences thin from below up to 25cm dia spacing of 3-6, between trees- remove all ladder fuels including trees >25cm with branches to ground – resulted evenly spaced open canopy – no wildlife considerations Nutriso (NU) – 2010 – more wildlife considerations based on public concerns – left some pockets of higher density and ladder fuels Planned for prescribed burning, but didn't happen before wildfire	2011 May 31-June 8 high fire hazard weather, driven by wind, slight downhill spotting distances 2.4 to 4.8 km	untreated 80—100% of trees at least partially consumed treated areas 0-25% partially consumed Bole char heights less in treated Fire intensity drops from crown fire at edge of treatment to <50% intensity based on bole char and crown scorch in: AG2 <100m AG6 <200m NU <450m in all treatment trees partially consumed dropped from 80-	create "speed bumps "to slow fire before it gets to WUI treatment areas leaving some clumps of untreated for wildlife are OK, but may locally increase fire intensity in the treated area

Author/Article	Study Area	Treatments	Wildfire	Outcomes	Comments
				100% to less than 25% within 50m	
Lyons-Tinsley and Peterson 2012 (also see Prichard et al. 2010 & 2011)	Tripod fire 2006 east edge of OK NF Assessment of young stands Pl, Se, Fd, Bl, Lw 10-30 yrs old	broadcast burn vs. no broadcast burn planted with mixed spp, but lots of infill as well	moderate to high severity fire mean temp 23.5, max 32.8 see also Prichard et al. 2010	Trtd Untrtd Bdcst Burn No burn # 25 19 mortality 37% 77% height m 3.1 3.4 dia cm 6.0 5.6 BA cm2/ha 30 49 dens st/ha 57 81 cnpy cls % 19.5 12.2	trt most important factor, but stand structure and spp. were also important in young stands lower canopy base ht leads to < mortality; higher crown closure leads to < mortality; influence of these factors may differ between trtmts good discussion of role of young stands in landscape mgmt
Martinson and Omi 2013 Meta-analysis of trtmts and fire severity	various fires based on 19 previous publications Primarily PNW and SW US (a few from C and NE US, Portugal, Australia) Long-needle pine forest Mixed conifer forest Woodlands other than conifer forest Grasslands	various treatments – in order of effectiveness: 1. Canopy thinned with slash and surface fuels reduced by burning or mechanical removal. 2. Canopy untreated, but surface fuels reduced by burning, mechanical removal, or grazing/browsing by livestock or other biological vectors. 3. Canopy thinned with no change to surface fuels via whole tree extraction. 4. Canopy untreated, but surface fuels rearranged by physical or chemical means (mastication,chipping, crushing, piling, herbicide application). 5. Canopy thinned with slash and surface fuels rearranged as above. 6. Canopy thinned with no treatment of the activity fuels added to the surface.	various conditions	effects of fuel trtmts on fire was large and significant: reduction of canopy volume scorch from 100 to 40%, scorch height from 30.5 to 16.1 m, and inferred flame length from 3.4 to 2.1 m significant variation depending on veg and trtmt types best effects in grasslands and conifer forest that were heavily thinned and underburned in the past year effects equally good in long needle pines and mixed conifer forests (no data for high elevations) negative impacts in oak woodland with mastication	surface fuel reduction is of primary importance some trtmts in some circumstances had counter-productive effects: 5/18 with untreated slash 1/3 masticated fuels 1/3 underburns >10 yrs old 1/17 with recent surface fuel reduction best predictor of surface fuel reduction effectiveness was residual tree dia. (likely due to greater height to canopy and thicker bark) excessive thinning provided no benefit beyond a threshold (ht. to

Author/Article	Study Area	Treatments	Wildfire	Outcomes	Comments
					canopy 9 m, mean dia. increased to >42 cm, canopy BD below 0.04 kg/m3) treatments change fire behavior, but do not stop fires
Martinson et al. 2003 in Graham 2003	Hayman Fire 2002 560 km2 C CO	various harvesting regimes, past fire histories and a few small fuel treatments	intense fast moving fire on one day and lesser intensity subsequent days	very mixed results of various treatments recent (<3 yrs) wildfires and prescribed burns were effective at changing fire behaviour but not stopping the fire; older wildfire areas were less effective	subjective descriptions only with high intensity fire small trtmt units are ineffective due to spotting
Martinson sand Omi. 2003 in Omni and Joyce 2003 Meta-analysis	Py, mixed conifer, slash pine 8 areas W US (WA, MT, CA,CO,AZ,NM) minor SE US (MS) RoNV fire return intervals: Py: 14-28 yrs Mix conifer: 52-59 yrs Slash pine: 9 yrs	thin thin, slash removed prescribed burn thin and burn pile and burn	various – not described	key variables in regression: treatment type treatment age reduction in stand density site – RONV fire frequency	fuel treatments reduced wildfire severity: e.g. crown scorch 84.5% vs. 38% but results were variable depending on site and treatment type thinning from below was most significant treatment factor
Moghaddas and Craggs 2007	Bell fire 2005 Plumas NF, N CA in extended WUI slope 11% Fd, incense cedar, Py, (Psugar, white fir, CA black oak)	158 ha; 1 yr old – on private land Thinned from 59 m2/ha and 1181 trees/ha using mark to leave trtmt to 181 t/ha; 23.7 m2/ha canopy base ht 9.2 m CC 36%; tree dia. 39.6 cm full tree harvest and mechanical removal of ladder fuels; tops and	small fire 14.2 ha RH 18% peak wind 16 km/hr	crown scorch in untrtd > 75% with torching cs decreased to <10% in trtd area within 60 m some spot fires in trtd area due to embers – 122 m into trtmt ignited slash, but flame length <0.6 m	fire easily contained by crews in trtmt area better penetration of retardant into trtd area due to thinned stand improved operations for fire crews – good visibility trtmt decreased

Author/Article	Study Area	Treatments	Wildfire	Outcomes	Comments
		biomass chipped and transported to cogen plant no surface fuel trtmt – but in photos looks very clean; no brush			suppression costs substantially
Petrakis 2018 remote sensing assessment	Creek Fire 2013 San Carlos Apache Reservation – E Central AZ Py forests; Fire RI 4-11 yrs Py woodland Py-Oak forest/ wdlnd Mesic and Dry-Mesic montane mixed conifer forest	1 Commercial harvesting 2 Harvest and thinning 3 Harvest with broadcast burning (all <40% slopes) 4 Resource benefit burn 5 Untreated "resource benefit burns" (managed wildfires) thinning was basically a fire treatment	7,311 ha; 6/16 – 7/7; lightning ignition weather was average, occurrence early in monsoon season not fought – treated as a resource benefit burn severity mainly low, but some patches of moderate to high	severity was worst in thinned and harvested areas (likely due to slash) untreated was intermediate resource burns and harvested with prescribed burns were best	used dNBR to assess burn severity
Pollet and Omi 2002 Abstract only	4 Py stands throughout the W US (WA,MT,CA,AZ)	Prescribed fire Whole tree thinning Thinning and prescribed fire	Unknown	Treated areas had significantly lower wildfire severity than untreated stands	Removing small trees is effective in reducing crown fire hazard
Prichard and Peterson 2010 Report See also: Prichard et al. 2010; Prichard and Peterson 2011 Lyons-Tinsley & Peterson 2011	Tripod fire 2006 see Prichard et al. 2010	see Prichard et al. 2010 no info on stand densities Thin Thin and prescribed fire Untreated	70,000 ha >60% moderate to high severity see Prichard et al. 2010	thinning alone did not have crown fire, but scorching and bole charring still killed trees due to slash load Tree Survival: All >20cm dbh Thin /burn 57% 73% Thin 19% 36% Untreated 14% 29%	noted that trtmts did not affect fire spread, but previous fire areas did influence spread good photos p10
Prichard and Peterson 2011 Report See also:	Tripod fire 2006 see Prichard et al. 2010 used dNBR from Landsat to assess burn severity	see Prichard et al. 2010	>73% was moderate and high severity spotting 0.5 to 1 km	areas treated with prescribed burns had lowest severity (+ thinning or cc'ing) areas with 10-20% canopy cover had lowest burn severity	analysis was able to separate day-to-day fire weather influence from fuel treatment influence

Author/Article	Study Area	Treatments	Wildfire	Outcomes	Comments
Prichard et al. 2010; Prichard and Peterson 2010; Lyons-Tinsley & Peterson 2011	fire mainly in Pl and ESSF forests, moderate to high elevations		areas recently burned in wildfires acted as fire guards or reduced severity; older fire areas were not as effective	(next lowest 0-10 and 20-30) MPB and spruce beetle attacks had mixed and/or weak effects treatment age was weakly & positively correlated with severity; 20-30 yrs increased severity by one class (likely due to slow succession) treatment size was weakly negatively correlated with severity; 200-300 ha decreased severity by one class due to spotting, treatments offered little protection to adjacent areas	
Prichard et al. 2010 Article	Tripod fire 2006 WA Eastern edge of Okanogan NF - NC WA mixed conifer: Fd, Py, Pl (Bg,Lw) slopes 18-53%	8 units thinned and 8 thinned and prescribe burned; no pile and burning in thinned only harvest within last 8-15 yrs and burning last 0-6 yrs mechanical harvest by thin from below and some shelterwood harvests 8-40 ha	extreme fire behaviour 21-29oC, RG 14-27%; winds 14-27km/hr; gusts to 40	tree survival 57% in thin and burn, 19% in thin and 14% in controls large trees (>20cm DBH) 73%,36%,29% mean crown scorch in thin and control >90%, 57% in thin and burn mortality Lw 21%, Py 39%, Se 88%, Fd 66%	in thinned only trees died due to scorch and bole char – not crown fire size of treatment unit did not seem to be important be careful about shrub increases with too much canopy opening
Raymond and Peterson 2005	Bisquit fire 2002 SW OR – Siskiyou NF 90-120 yr old stand with natural fire frequencies of 90-150 Overstory Fd with some knobcone pine and sugar pine – subcanopy of	thinned in 1996 small plots 6-8 ha, one site had 15% of logs left as CWD thinning from below with some crown removal left only Fd, snags were left broad leaf trees to 8m spacing 1000-1440 st/ha thinned to about 200-400 st/ha	26oC and RH of 8% and fine fuel at 4%; ave. wind 4km/hr on the day sites burned' fire weather indicated severe fire behaviour	fire damage was greatest in thinned stands (80-100%) and least in thinned and underburned stands (5%) – untreated were intermediate (53-54%)	high intensity ground fire can cause heavy mortality in the absence of a crown fire per se % crown scorch was a good predictor of mortality thinning may have increased wind exposure

Author/Article	Study Area	Treatments	Wildfire	Outcomes	Comments
	tanoak, arbutus and chinquapin and smaller Fd moderate slopes 10-35%		mostly surface fire		and increased fire intensity
Ritchie et al. 2007 see also Agee and Skinner 2005; Symons et al. 2008	Cone fire 2002 see Agee and Skinner 2005	thinning from below with and without prescribed fire trtmts with BA from 8.4 -25.9 m2/ha and 137 to 246 st/ha	RH of 6% Wind gusts to 51km/hr see Agee and Skinner 2005	treatments with prescribed fire performed better, but even wo/ crown fires were converted to surface fire w/in 25m of trtmt boundary	trtmts can remain effective up to 20 yrs in dry Py types
Safford et al. 2012	12 fires CA 2005-2011 Py and mixed conifers transects from untrtd into trtmts	removal and burning of ladder and surface fuels mechanical plus prescribed fire/pile burn (1) commercial (c) thin + precommercial thin (pc) + unknown; (2) c thin (whole tree yarding); (3) c thin + pc thin + hand pile + pile burn; (4) pc thin + hand pile + underburn; (5) c thin (whole tree) + underburn; (6) c thin + pc thin + underburn; (7) pc thin; (8) salvage harvest + pc thin + chipping + underburn; (9) c thin + machine pile + pile burn. trtmts 1 to 9 yrs old	warm dry conditions with high winds 112 – 15,000 ha all fires slightly different 2 low intensity fires under cooler conditions had similar results in trtd and untrtd	fuel moisture better predicted fire severity in untreated, while fuel loading was the best predictor in treated stands most canopy fires were reduced to surface fires within 70m of trtmt edge no effect of treatment age (1-9 yrs); speculate 15-20 yrs will affect larger trees had better survival slope had a greater effect in treated areas – increased slope increased impacts Py,Pjeff best survival, Fd and Quercus kelloggii good no need for further studies – it works!	need treatment width of ~ 400-500m with extreme fire weather due to rate of spread and response time to allow fire fighters to put fire out (worse with embers) removal of ladder and surface fuels are effective non-removal of trtmt fuels leads to greater fire severity burning piles and/or broadcast burning is superior to mastication expect 5-15% mortality in treated areas
Safford et al. 2009	Angora fire 2007 Lake Tahoe basin CA 1900-2300 m elev Jeffery pine, white fire, red fir, incense cedar and sugar pine and Pl	194 ha of trtmts 2 trtmts partially failed due to lesser removal of fuels due to steep slopes and piles had not yet been burned	1243 ha very high severity strong winds warm dry weather dry fuels 254 houses	crown fires to ground fires within 50m of trtmt edge need greater fuel removal on steep slopes to get same effect	need FireSmart treatments in addition to fuel treatments

Author/Article	Study Area	Treatments	Wildfire	Outcomes	Comments
Schroeder 2010	Pb (Sb) in NW territories (jack pine)	Thinning from below to: 500 st/ha 4.1m spacing 3.6 m between crowns Crown BD 0.07 kg/m3 Ht. to Crown base 9.8 m thinnings were mechanically removed from site	2 experimental prescribed crown fires in adjacent untreated stands wind driven into treatment area back winds of 10-15 km/hr	Crown fire dropped to the ground upon entering the treated area ROS dropped from 20-40 m/min to about 1m/min (most rapid on site with reindeer lichens) Spotting distances 70-175 m A few torched trees near the edge of treatment Crews easily extinguished fire 25-30 m into the treated area	Excellent experiment! Based on modeling, to reach an 80% probability of crown fire – untreated only needed 5 km/hr wind, treated required about 24 km/hr
Symons et al 2008 See also Richie et al. 2007; Agee and Skinner 2005	Cone Fire Lassen Nat. Forest NE CA Py, Pjeffrey (white fire, incense cedar)	Mechanical thinning w/ and wo/ prescribed fire Trtmts 2-5 yrs old; 100 ha trtmt areas 1 High Diversity – retain large trees, snags, multiple canopy layers w/ clusters of small trees/ openings 2 Low Diversity – retain single layer of intermediate trees (remove large trees, snags and small trees)	See Richie et al. 2007; Agee and Skinner 2005	**All** treatments converted crown fire in untrtd to surface fire in trtd areas Mortality–90% untrtd, 18% trtd LD treatment with prescribed fire was most effective in reducing fire severity HD w/fire and LD wo/fire were somewhat effective – but for different reasons (ladder fuels vs. surface fuels) Bole Scorch (%, m into trtmt) 0-50 50-100 100-150 HDwF 87 34 3 LDwoF 69 2 0 LDwF 52 8 4 Crown Scorch (%, m into trtmt) 0-50 50-100 100-150 HDwF 100 98 20 LDwoF 97 4 3 LDwF 82 27 8	Excellent discussion of the role of ladder fuels and surface fuels

Author/Article	Study Area	Treatments	Wildfire	Outcomes	Comments
Thompson and Spies 2009	Bisquit fire 2002 see Raymond and Peterson 2005	None – assessment of vegetation, topography and geology affecting severity of conifer damage shrubs of huckleberry oak, manzanita and snowbrush (Ceo velutinous)	see Raymond and Peterson 2005	Areas with dense shrubs had higher impacts of conifer damage	Previous fire history had no effect or maybe increased severity due to resprouting, shrubs and regrowth (1987)
Thompson et al. 2011	Bisquit fire 2002 see Raymond and Peterson 2005	198 plantations of various ages (5-47) Fd (Py, sugar pine) 1.25-47 ha plantations	see Raymond and Peterson 2005	canopy damage ave was 77% - age was most important factor on degree of damage – greatest damage between 15-25 yrs old other significant factors: annual precip, elev and topo position (toe slopes/ depressions least damage)	young plantations do burn under the right conditions
Waltz et al. 2014	Wallow fire 2011 AZ	see Kennedy and Johnson 2014	see Kennedy and Johnson 2014	before fire Trtd 219st/ha 14.3m2/ha Untrtd 1093st/ha 33.4m2/ha after fire Trtd 83st/ha 9.8m2/ha Untrtd 292st/ha 15.3m2/ha trtd areas retained more large trees, had densities within RoNV, higher cover of native grasses, less number and smaller high severity burn patches (sev=overstory mortality and basal area loss) – 6 times less trees killed	trtmts increase ecosystem resiliency
Wimberly et al. 2009 remote sensing assessment	Camp 32 Fire, W MT 2005 Fd, Py, (Lw) 50-150 yrs BA 6.9 to 23 m2/ha School Fire, SE WA Py, Fd, Lw (Bg	Camp 32 1) thinning (dia cut <30 cm, BA to 13.8m2/ha lots of slash), in progress 2) thinning (dia cut <30 cm, BA to 6.9 to 9.2 m2/ha) and prescribed fire; completed 1-3 years before wildfire School	Camp 32 – about 20,000 ha School – rapid spread first day (12,000 ha), then slower Warm – 23,500 ha	Camp 32 severity was worst in thinned (likely due to slash)and least in thinned and prescribed burned School burn severity was least in thinned and prescribed burned;	used dNBR to assess burn severity analysis was able to separate day-to-day fire weather influence from fuel treatment influence partial fuel treatments

Author/Article	Study Area	Treatments	Wildfire	Outcomes	Comments
	understory) 50-190 years BA 3-27.1 m2/ha Warm Fire N AZ 2005 Py, At (Fd, Bc); some areas of Pp - juniper	1) prescribed burning 2) thinning 3) thin and prescribed burn (part broadcast and part pile and burn) Warm 1) shelterwood (sparse scattered trees) 2) prescribed burn (understory removal) 3) thinning (from below to 20.7 m2/ha; 65% piled slash. 35% scattered slash)	in 26 days; began slowly then rapid advance for 2 days	and slightly less in thinned than untreated; prescribed burning alone was not different from untreated Warm prescribed burning alone and shelterwood has less severity; thinning alone increased severity over untreated	without prescribed burning or pile and burning was shown to make fire severity worse

Table A1-2. A sampling of modelling studies that assessed potential efficacy of various fuel treatments.

Author/Article	Study Area	Treatments	Wildfire	Outcomes	Comments
Ager et al. 2010	NE OR	Modeling of benefits of treatments n the WUI vs. restoration trtmts in other areas	NA	Benefits vary depending on where you treat	Lots of offsite benefits no matter where treatments are done
Chung 2015	NA	Review of previous modeling studies that attempted to optimize treatment type, timing and location	NA	Need for flexibility in prescriptions to work in varying landscape contexts	Planning is complex
Fule et al. 2002	Kaibob NF AZ Py (Juniper, P edulis, Gambel Oak)	Full – thinning to RONV, treat fuels, prescribed fire: tree density down 89%,1340 st/ha to 154 st/ha (BA from 17.5 to 6.2m2/ha) Min – minimal thinning – 12-18 m around OG and trees: prescribed burn; density down 77% from 2935 st/ha to 684 st/ha (50% thin, 50% fire etc) BA from 22.5 to 13.4 m2/ha raking of fuels from around full and min OG trees for retention Burn - burn only (density down 63% (3690st/ha to 1384) BA from 27.0 to	simulated 90th and 97th percentile fire conditions	Heavy thinning and burning reduced fire severity more than light thinning and burning or burning alone	good discussion of restoration and some habitat issues

Author/Article	Study Area	Treatments	Wildfire	Outcomes	Comments
		21.7m2/ha Control			
Hurteau et al. 2016 Treatment and wildfire scenario modelling	Py dry forest types NC AZ	No treatment, thin, thin and prescribed burn	Modeled 0%, 1% and 2% of area burned per year	Although ecosystem carbon storage initially decreased with trtmt, it was greater in the long run with wildfire (40-50 yrs to recover); trtmts reduced wildfire severity	Higher productivity ecosystems may show less increase or no increase
Johnson et al. 2007 Guide to trtmts based on modelling	Various dry forest types in W US – includes types from WA and MT that are relevant to S WK	various combinations of thinning, surface fuel treatments and prescribed burns – looks at various levels of thinning (retention of 80 to 480 st/ha)	NA	Various levels of crown fire risk, levels of Crown BD, etc. Demonstrates that moderate levels of retention are not problematic for crown fire risk	Good visualizations and detailed info on stand development and fuel changes after treatments
Johnson et al. 2011	modeling	thinning to various densities and thinning combined with surface fuel treatments four density reductions – thin to 750, 500, 250 125 st/ha surface fuel treatments – none, slash removal, prescribed fire	NA	prescribed burning was shown to be best surface fuel treatment; but mechanical not much better than no treatment on some sites – authors thought model needed updating	thinning to 125-250 stems/ha was better than 500-750
Jones et al. 2017	modeling watershed erosion w and wo/ trtmts		NA	can be positive return on investment to protect watersheds against erosion costs resulting from wildfire	

Table A1-3. Miscellaneous articles providing background on the concept of fuel treatments and other issues related to treatments.

Author/Article	Study Area/ Applicability	Topic Focus/ Treatments	Outcomes	Comments
Fialko 2018 MS Thesis; post-trtmt regen Fd &	Pike-San Isabel and Arapaho-Roosevelt NF – NW/SW of Denver CO	mastication – resid density ave 173 t/ha – 14.0 m2/ha thinning – product removal, lopped and	S aspects more Py, north aspects more Fd 37% had no regen and 41%	aspect and spp composition, % CC, and time since trtmt affect amount and type of regen trtmt type didn't seem to be controlling regen

Author/Article	Study Area/ Applicability	Topic Focus/ Treatments	Outcomes	Comments
Py	1850-2200 m Fd/Py and Fd with Pl, Se, Pflex, At	scattered, piled, and/or piled and burned resid density ave 240 t/ha – 14.2 m2/ha seemed to have left lots of Fd advanced regen in many areas (2/3s of regen) missed by treatment ?? 5 to 14 yrs since treatment 227 plots	<10; 4% >30 (up to 181) 71% Fd 17.5% Py (Pl, Se, Pflex, RM juniper 4-5 times more regen on N aspects 5 times more regen in 11 yr old plots compared to 5 yr old	Fd regen favoured with more shade, Py with more open Trtmt will require more maintenance on N aspects
Hicke et al. 2012	beetles and wildfire based on lit review of modeling and observations of wildfire in beetle areas	NA	NA	time since beetle attack is a key factor good diagrams of risk
Jain et al. 2012 Guide to Fuel trtmts	N Rocky Mtns included – similar to S WK Western Dry forests	General background on fire regimes, climate, fuels, past mgmt., treatment planning, wildlife habitat considerations, treatment methods, monitoring and maintenance	Good summary of available info to date	Exhaustive info on planning trtmts; info on planning process, wildlife habitat implications and tree spp. tolerances
Keller 2011 Brochure for public	Wallow fire 2011 see Kennedy/ Waltz	see Kennedy/ Waltz	see Kennedy/ Waltz	shows how treatments protected structures great photos
Kennedy and Fontaine 2009	Across the US	Wildlife responses to wildfire and wildfire surrogate treatments	Summary of studies of individual spp. population responses	Information on the different wildlife response studies, time since disturbance, type of disturbance, and different wildlife types [amphibian, raptors, birds, bat, small mammal, and large mammal.
McIver et al. 2013	7 sites in W US and 5 in E US Py/Fd – fire return interval 5-25 yrs C WA, N,C,C CA, W MO, NE OR, N AZ	objective for all treatments was to achieve stand and fuel conditions such that, if subjected to a head fire under the 80th percentile weather conditions, at least 80% of the basal area of the dominant and co-dominant trees would survive (80/80 rule) trials with thinning, thinning and burning	discussion of potential fuel changes only few negative ecological impacts (loss of CWD and snags in some areas, potential interactions with beetles, invasive spp)	mechanical or prescribed burning alone can work on some sites, but mechanical with prescribed burning is best trtmts – especially burning – need to be repeated for maintenance extensive discussion of habitat and ecological impacts

Author/Article	Study Area/ Applicability	Topic Focus/ Treatments	Outcomes	Comments
		and burning, control	long-term study may be needed	
North et al. 2019	Dry western US forests	Reforestation strategies to increase climate change resilience: resilience to wildfire and drought	Importance of assessing natural patterns of regeneration following stand-replacing disturbances	Emphasis on the need to vary regen density to mimic natural patchiness; planting to standard densities will not be successful; consider using prescribed fire early in stand development
Pilliod et al. 2006	Dry forest types in Western US	Impacts of fuel treatments on wildlife habitat features	Open forest spp. benefit, closed forest spp. may be detrimentally impacted	Maintenance of snags, CWD and untreated patches within trtmt area are important considerations
Prichard and Kennedy 2012	Tripod fire (see Prichard et al. 2010)	Control Thin only Thin and prescribed fire	3 yrs after fire mortality was: Control 78% Thin 65% Thin and burn 43%	Fire mortality was least in Py Post-fire beetles tended show a preference for larger trees Thinning combined with prescribed fire trtmt reduced risk of subsequent beetle attacks
White et al. 2018	Science Update – general summary of treatments and efficacy	NA	recommendation of 120 – 250 st/ha for effective treatments	good simple information suitable for general public – excellent illustrations

Appendix 2: References and Background on Treatment Targets

No single reference necessarily matches the recommendations above; however, the following sources provide some useful information that contributed to the individual targets:

- Stems/ha, ï various results in Appendix 1
- Basal Area ï Hessburg et al. 2016 and results in Appendix 1
- Crown Bulk Density ï Peterson et al. 2005, Scott and Reinhardt 2001, Hessburg et al. 2016
- Crown Closure ï Prichard and Peterson 2011 and results in Appendix 1
- Canopy base height ï Peterson et al. 2005, Scott and Reinhardt 2001, and results in Appendix 1
- Retained tree species and diameter ï Agee and Skinner 2005, Tepley et al. 2013, Belote et al. 2015 and results in Appendix 1

Table A2-1. Examples of estimated canopy bulk density (kg/m3) for 3 species by diameter and density; (Py Ponderosa pine, Fd Douglas fir, Bg Grand fir; diameters converted from Imperial, hence odd sizes. Green are under the 0.04 kg/m3 target, orange are within the acceptable range under 0.08 kg/m3. These are based on single species non-stratifed stands – multi-species stands with stratified crowns may have greater BD's (adapted from Agee 1996).

Ave. dbh		Density - Trees/ hectare (st/ha)				
(cm)	spp.	50	100	200	400	800
	Py	0.001	0.002	0.005	0.009	0.018
1.3	Fd	0.002	0.003	0.005	0.011	0.022
	Bg	0.002	0.003	0.007	0.014	0.027
	Py	0.003	0.007	0.014	0.028	0.055
7.6	Fd	0.004	0.007	0.014	0.028	0.056
	Bg	0.012	0.024	0.047	0.012	0.094
	Py	0.005	0.010	0.021	0.041	0.083
19	Fd	0.009	0.017	0.034	0.068	0.136
	Bg	0.008	0.016	0.033	0.066	0.132
	Py	0.010	0.020	0.041	0.082	0.164
32	Fd	0.012	0.025	0.049	0.099	0.198
	Bg	0.013	0.026	0.052	0.103	0.206
	Py	0.011	0.023	0.047	0.095	0.190
44	Fd	0.019	0.039	0.078	0.155	0.310
	Bg	0.023	0.047	0.095	0.190	0.247
	Py	0.031	0.062	0.124	0.248	0.361
64	Fd	0.023	0.048	0.096	0.191	0.252
	Bg	0.023	0.047	0.095	0.247	0.247
	Py	0.033	0.066	0.133	0.194	-
102+	Fd	0.042	0.083	0.167	0.210	-
	Bg	-	-	(no data)	-	-

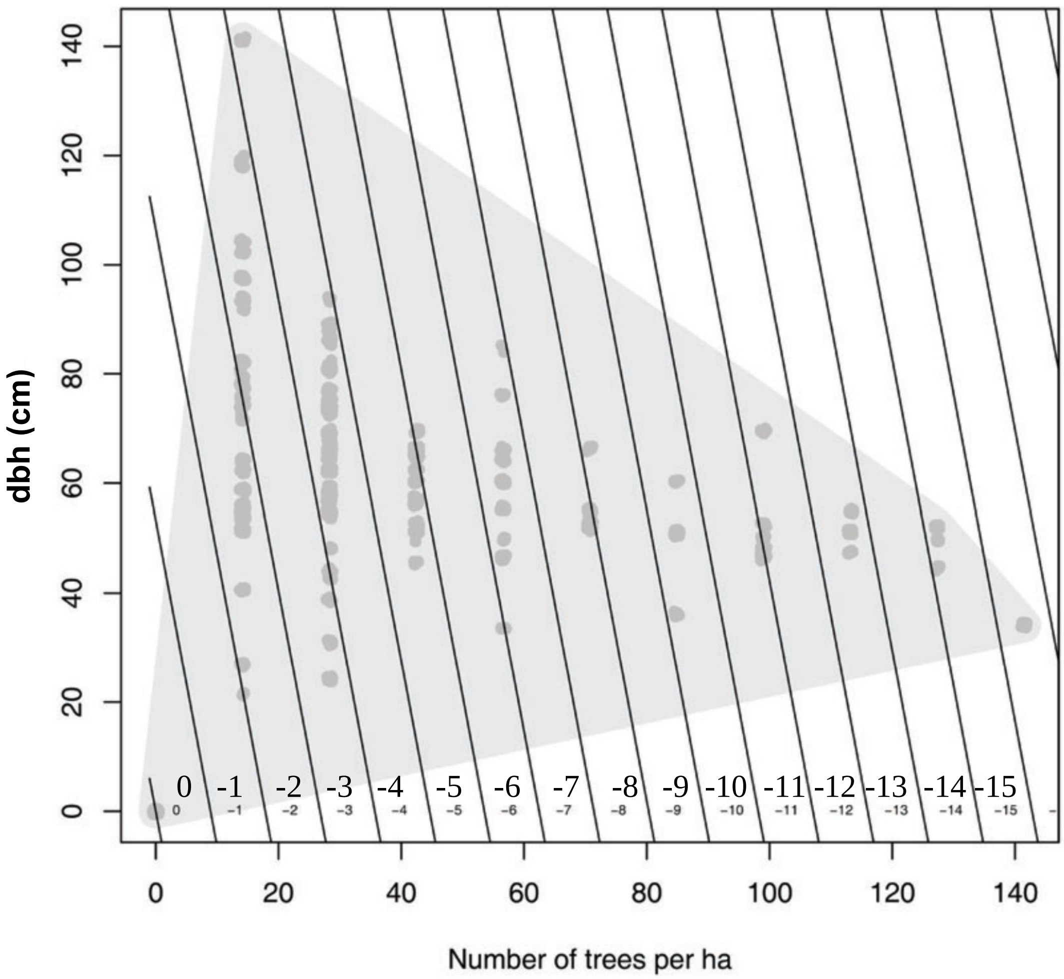

Figure A2-1. Fuels treatments that resemble thinnings or shelterwood harvests will vary in their suppression of ladder fuel development over time, depending on the number and sizes of trees retained following treatment. Data from a variable-retention study in central Oregon dry mixed conifer forests dominated by ponderosa pine are used here to model that relationship. The overstory tree sizes (dbh Y-axis) and density (trees per hectare; X-axis) together determine the suppression of regeneration height growth rates. The diagonal lines denote the projected reduction in ladder fuel height growth (meters) over 100 years, relative to open-grown trees at the same site. (adapted from Jain et al. 2012, p229).

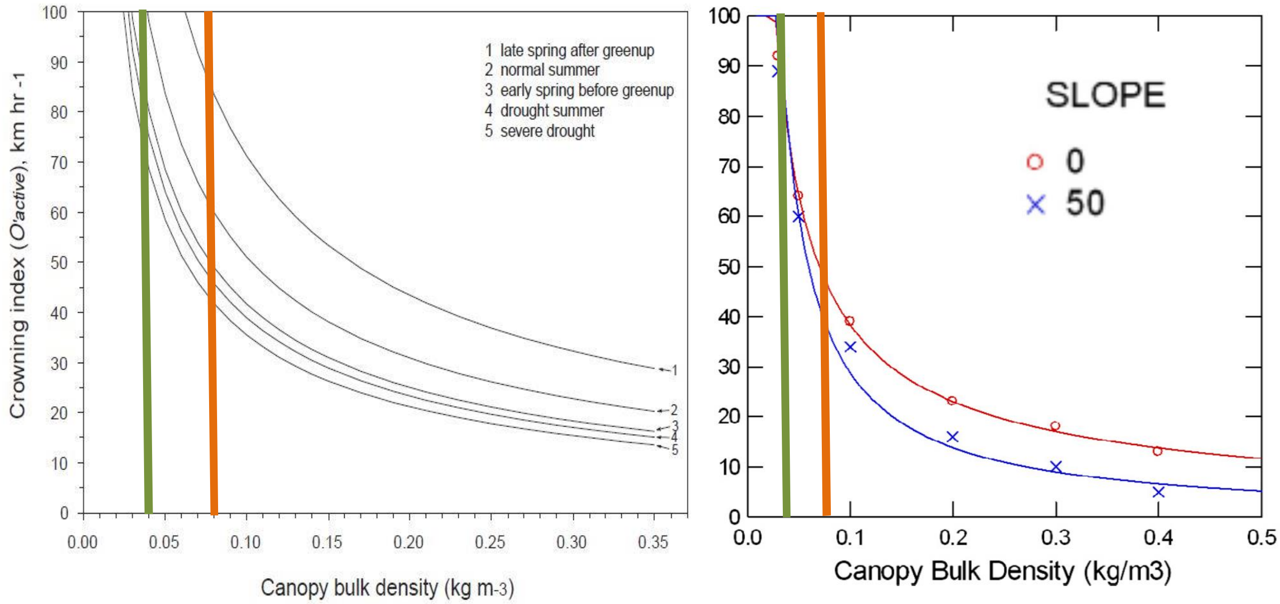

Figure A2-2. Relationship between canopy bulk density, seasonal moisture levels, b) slope, and wind speeds necessary to propagate an active crown fire (adapted from Scott and Reinhardt 2001 and Hessburg et al. 2016). Green vertical line is target of 0.04 kg/m3, and orange line lower acceptable level of 0.08 kg/m3.

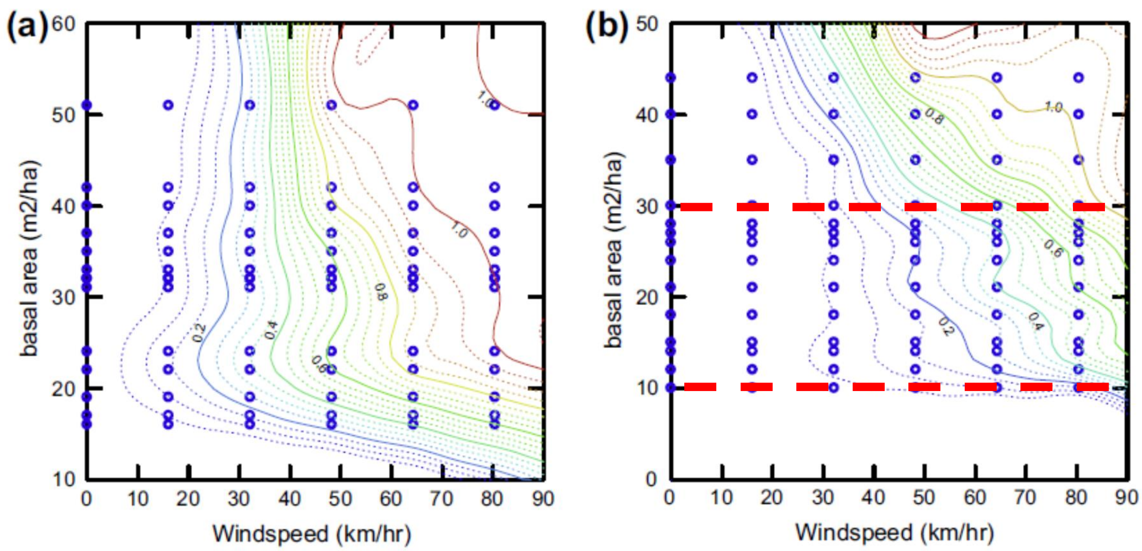

Figure A2-3. Canopy fraction burned as a function of stand basal area (BA) and wind speed for two scenarios on the eastern slopes of the Oregon Cascades. This figure (a) is from 13 forest plots with measured crown bulk density (CBD), crown base height (CBH), and BA. This figure (b) is from the same plots but with all trees less than 20 cm DBH excluded from the CBD, CBH, and BA calculations (simulating a low thinning). Isolines represent modeled crown fraction burned, assuming late summer fuel moistures and using actual plot slope (which ranged from 0% to 13%). Circles represent simulated combinations of BA and wind speed. Notice in this example that canopy fraction burned at a given wind speed becomes strongly dependent on basal area. This will often but not always be the case. Exceptional examples will include true firs with relatively low CBH values, and stands with low BA, but significant ladder fuels (from Hessburg et al. 2016,p236). The red dashed lines indicate the recommended target range.

		BA (m2/ha)	BA (m2/ha)	Crown 3m dia.		Crown 5m dia.	
St/ha	Spacing	25 cm dia.	50 cm dia.	CC %	Separation	CC %	Separation
64	12.5 m	3.2	12.6	4.5%	9 m	12.6%	8m
100	10.0 m	4.9	19.6	7.1%	7 m	19.6%	5 m
144	8.3 m	7.1	28.3	10.2%	5 m	28.3%	3 m
196	7.1 m	9.6	38.5	13.9%	4 m	38.5%	2 m

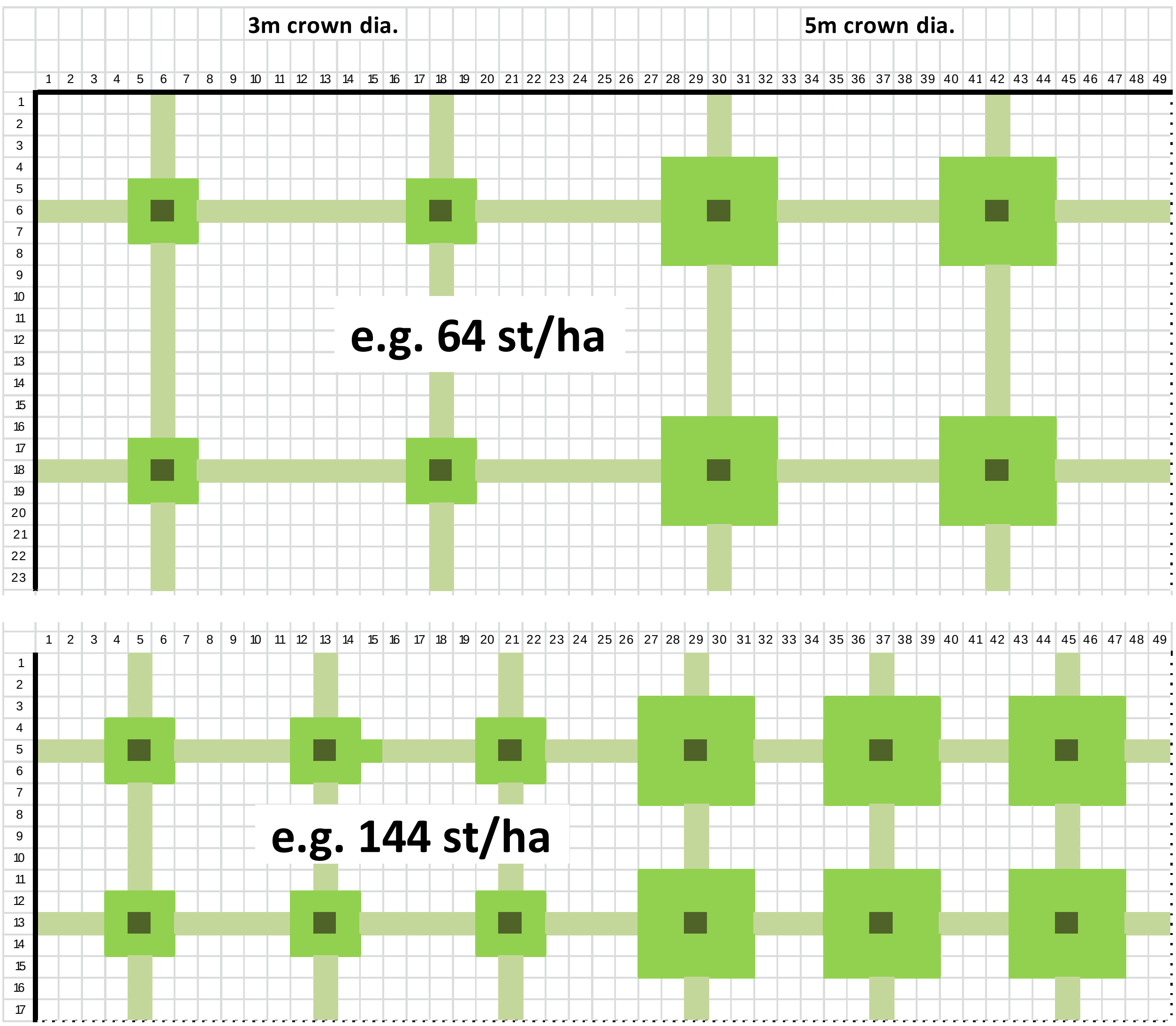

Figure A2-4. Examples of interactions between tree canopy diameter, stand density, crown closure and canopy separation.

Appendix 3: Example of a Basic Treatment Planning Process